



Universidad del País Vasco Euskal Herriko Unibertsitatea

Departamento de Ingeniería de Comunicaciones
Komunikazioen Ingenieritza Saila
Department of Communications Engineering

Doktorego Tesia

Potentzia Domeinuko NOMA
5G Sareetarako eta Haratago

Egilea: Eneko Iradier Gil

Zuzendariak: Dr. Jon Montalban Sanchez
Dr. Pablo Angueira Buceta

2021eko uztaila

*Tesi hau bide honetan zehar
nire ondoan egon diren
pertsona guztiei eskainia dago.*

Laburpena

Azken hamarkadan, haririk gabeko sareetan garraiatzen den datu kopurua esponenzialki hazi da. Hainbat arrazoik eragin dute egoera hori, baina eragin handiena izan dutenak sarera konektatutako gailuen hedapen masiboa eta eskaintako zerbitzu moten etengabeko bilakaera izan dira. Izan ere, gero eta gehiago dira duela urte batzuk futuristiko gisa planteatzen ziren aplikazioak, orain errealitate bihurtu direnak, besteak beste errealitate areagotua edo errealitate birtuala.

Aplikazio multzoa sailkatzeko, International Telecommunication Union (ITU-R) erakundearen irrti-komunikazioen sektoreak hiru erabilera-kasu nagusi definitu ditu aplikazioak taldekatzeko: Enhanced Mobile Broadband (eMBB), Ultra-Reliable low Latency Communications (URLLC) eta massive Machine Type Communications (mMTC). Erabilera-kasu horietako bakoitza beharizan eta baldintza desberdinak betetzera bideratuta dago. Adibidez, eMBB entretenimenduko eta informazioko multimedia-zerbitzuetarako ahalmen handiak eskaintzera bideratuta dagoen bitartean, URLLC sistemetan fidagarritasun-tasa altuak eta latentzia baxuak behar dituzten aplikazio kritikoak daude. Bestalde, mMTCk, neurri handi batean, Internet of Thing (IoT) sareak eta haririk gabeko sentsoreen sareak ordezkatzeko, non erabiltzaile-dentsitate oso altuekin lan egin behar den.

Erabilera-kasuetan integratutako aplikazio guztiak behar bezala inplementatzen direla bermatzeko jaio da 5G, komunikazio mugikorren estandar gisa ez ezik, teknologien, tekniken eta estandarren ekosistema gisa ere ulertu behar dena. Nahiz eta azken komunikazio-estandarrek hobekuntza berritzaileak izan, hala nola kodifikazio eraginkorragoa edo uhin-forma malguak, ITU-R-ek aipatutako aplikazioak gauzatzeko erronkarik handiena eraginkortasun espektrala hobetzea da. Horrela, eskaintako gaitasuna eta aldi berean konektatutako erabiltzaileen kopurua hobetu ahal izango da.

Tesi honetan, modu konbinatuan bi mekanismo erabiltzen dira eraginkortasun espektrala hobetzeko: Non-Orthogonal Multiple Access teknikak (NOMA) eta Radio Resource Management eskemak (RRM). Zehazki, lehenengoa datu-fluxuak gainjartzean datza, banda-zabalera osoa erabil dadin aldi berean zerbitzu bat baino gehiago bidaltzeko. Bigarrena, berriz, irrti-baliabideak sareko erabiltzaileen artean eraginkortasunez banatzean eta kudeatzean oinarritzen da. Nahiz eta NOMA tekniken eta RRM eskemen erabilera oso onuragarria izan daitekeen erabileraren kasu guztietan, kontuan izanik tesiaren iraupena mugatua dela, ez da bideragarria hain irismen zabala ezartzea. Hori dela eta, tesi honen ardatza eMBB eta URLLC inguruneetan ekarpenak egitea da, baita 6Gn

garrantzitsuak izatea espero den komunikazioei irtenbideak proposatzea ere.

Lehenik eta behin, NOMA erabiltzea proposatu da, eMBB aplikazioetan broadcast edukien transmisioa bermatzeko mekanismo gisa. Horretarako, beharrezko arkitektura definitu da eta software-prototipo bat eraiki da. Broadcast edukiaz gain, haririk gabeko sareetan unicast eduki-bolumen handia dago, eta, horregatik, bi zerbitzuen konbergentzia-sistema bat diseinatu da, aldi berean bana daitezen. Ondoren, NOMAn oinarritutako zenbait RRM eskema diseinatu dira, non konbergentzia hori ere kudeatu den. Azkenik, lortutako ezagutza erabilera espezifikogoko kasuetan aplikatu da, hala nola erabiltzaileak taldekatzeko tekniketan eta hari gabeko komunikazioetan frekuentzia milimetrikoen bandan.

URLLCri dagokionez, NOMAn oinarritutako zerbitzuek eskaintzen duten irabazia hainbat parametro hobetzera bideratu da, besteak beste, fidagarritasuna, ahalmena edo latentzia. Lehenengo lanean, aplikazio industrialetarako NOMAn oinarritutako Wi-Fi transtzeptore-prototipo bat diseinatu da, gaur egun aplikazio industrial gehienek beren Wi-Fi sareak erabiltzen baitituzte. Era berean, fidagarritasunean irabazi ahal izateko, birtransmisio-eskema desberdinak aztertu eta ezarri dira, eta espazio aniztasuneko eskemak nabarmentzen dira. Azkenik, RRM eskemetan NOMA erabiltzearen eragina ere aztertu da, eta teknika ortogonalekin alderatuta errendimendua hobetzen dutela zehaztu da, bereziki aplikazioaren eta sarearen eskakizunak zorrotzagoak direnean.

Azkenik, full-duplex komunikazioen esparruan ikertu da; izan ere, etorkizuneko komunikazio-estandarretan garrantzi handia izango dutela espero da, espektro-eraginkortasuna nabarmen handituko delako. Kasu honetan, broadcast edukiaren frekuentzia-banda berean banaketa-seinalea integratzen duen sistema bat diseinatu da. Eskema hau Estatu Batuetako telebista digitaleko estandarrean (ATSC 3.0) oinarrituta dago eta LDM, NOMA teknika espezifikoa, erabiltzen du, banaketa-seinalearen eta eduki tradizionalaren arteko multiplexazio-mekanismo gisa. Era berean, sistemaren bilakaera gisa, telebista-seinalea banatzeaz arduratzen diren transmisoreak elkarrekin konektatzeko arkitektura diseinatu da. Azkenik, ekarpen horri lotutako erronka garrantzitsuenak identifikatu dira, eta epe laburrean frogatuko diren irtenbideak planteatu dira.

Abstract

During the last decade, the amount of data carried over wireless networks has grown exponentially. Several reasons have led to this situation, but the most influential ones are the massive deployment of devices connected to the network and the constant evolution in the services offered. In fact, there are several applications that a few years ago were considered futuristic and that have now become a reality, such as augmented reality or virtual reality.

In order to classify the set of applications around 5G networks, the radiocommunications sector of the International Telecommunication Union (ITU-R) has defined three prominent use cases: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC). Each of these use cases is oriented to cover different connectivity needs with different requirements. For example, while eMBB offers high capacity to multimedia entertainment and information services, URLLC gathers critical applications that need high reliability rates and low latency. For its part, mMTC represents, to a large extent, Internet of Thing (IoT) networks and wireless sensor networks where a very high number of user/device connections is the major challenge.

In this context, 5G targets the correct implementation of every application integrated into the use cases. 5G must be understood not only as a standard for mobile communications but as an ecosystem of technologies, techniques, and standards. These latest communication standards present significant advances, such as more efficient coding or flexible waveforms. Nevertheless, the biggest challenge to make ITU-R defined cases (eMBB, URLLC and mMTC) a reality is the improvement in spectral efficiency. In this way, it will be possible to improve both the capacity offered and the number of users connected simultaneously.

In this thesis, a combination of two mechanisms is proposed to improve spectral efficiency: Non-Orthogonal Multiple Access (NOMA) techniques and Radio Resource Management (RRM) schemes. Specifically, NOMA transmits simultaneously several layered data flows so that the whole bandwidth is used throughout the entire time to deliver more than one service simultaneously. Then, RRM schemes provide efficient management and distribution of radio resources among network users. Although NOMA techniques and RRM schemes can be very advantageous in all use cases, this thesis focuses on making contributions in eMBB and URLLC environments and proposing solutions to communications that are expected to be relevant in 6G.

First, NOMA has been proposed as a mechanism that guarantees the transmission of broadcast content in eMBB applications. For this, the

necessary architecture has been defined, and a software prototype has been built. Apart from broadcast content, in wireless networks, there is a large volume of unicast content. For this reason, a convergence system of the two services has been designed so that they can be distributed simultaneously. Subsequently, different RRM schemes based on NOMA have been designed, where the convergence has also been managed. Finally, the knowledge obtained has been applied to more specific use cases, such as user subgrouping techniques and wireless communications in the millimeter frequency band.

Regarding URLLC, the gain offered by the services based on NOMA has been oriented to improve different parameters, such as reliability, capacity, and latency. In a first work, a Wi-Fi transceiver prototype based on NOMA has been designed for industrial applications. Likewise, in order to increase the reliability gain, different retransmission schemes have been studied and implemented, in which spatial diversity schemes stand out. Finally, the influence of using NOMA in RRM schemes has also been studied, and it has been found that they improve the overall performance compared to orthogonal techniques, especially when the application and network requirements are high demanding.

Finally, this thesis has contributed to in-band full-duplex communications. It is expected that in-band full-duplex solutions will have great relevance in future communication standards due to their considerable increase in spectral efficiency. In this case, a system that integrates the distribution signal in the same frequency band of the broadcast content has been designed. This scheme is based on the American digital television standard (i.e., ATSC 3.0) and uses LDM, a specific NOMA technique, as a multiplexing mechanism between the traditional content and the distribution signal. Furthermore, as a system evolution, an architecture has been designed to interconnect the transmitters in charge of distributing the television signal. Finally, the most relevant challenges associated with this contribution have been identified, and solutions to be tested in the short term have been proposed.

Resumen

Durante la última década, la cantidad de datos que se transporta en las redes inalámbricas ha crecido exponencialmente. Son varios los motivos que han propiciado esta situación, pero los que más han influido son el despliegue masivo de dispositivos conectados a la red y la constante evolución en los tipos de servicios ofertados. De hecho, cada vez son más las aplicaciones que hace unos años se planteaban como futurísticas y que ahora se han convertido en realidad, como la realidad aumentada o la realidad virtual.

Con el fin de clasificar el conjunto de aplicaciones, el sector de radiocomunicaciones de la International Telecommunication Union (ITU-R) ha definido tres grandes casos de uso en los que agrupar las aplicaciones: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC) y massive Machine Type Communications (mMTC). Cada uno de estos casos de uso está orientado a cubrir diferentes necesidades y bajo diferentes requisitos. Por ejemplo, mientras que eMBB está orientado a ofrecer grandes capacidades para servicios multimedia de entretenimiento e información, en URLLC se encuentran las aplicaciones críticas que necesitan altas tasas de fiabilidad y bajas latencias. Por su parte, mMTC representa, en gran medida, a las redes Internet of Thing (IoT) y las redes de sensores inalámbricos donde se debe trabajar con densidades de usuario muy altas.

Para garantizar la correcta implementación de todas y cada una de las aplicaciones integradas en los casos de uso nace 5G, que debe entenderse no solamente como un estándar de comunicaciones móviles, sino como un ecosistema de tecnologías, técnicas y estándares. A pesar de que los últimos estándares de comunicaciones presentan novedosas mejoras, como codificación más eficiente o formas de onda flexibles, el mayor reto para poder hacer realidad las aplicaciones mencionadas por la ITU-R es la mejora en la eficiencia espectral. De esta manera, se podrá mejorar tanto en la capacidad ofrecida como en la cantidad de usuarios conectados simultáneamente.

En esta tesis, se utilizan de manera combinada dos mecanismos para mejorar la eficiencia espectral: técnicas Non-Orthogonal Multiple Access (NOMA) y esquemas Radio Resource Management (RRM). En concreto, el primero consiste en utilizar superposición de flujos de datos para que se aproveche todo el ancho de banda durante todo el tiempo para enviar más de un servicio al mismo tiempo. En cambio, el segundo se basa en la gestión y reparto eficiente de los recursos radio entre los usuarios de la red. A pesar de que el uso de las técnicas NOMA y los esquemas RRM puede ser muy ventajoso en todos los casos de uso, teniendo en cuenta que

la duración de la tesis es limitada no es viable establecer un alcance tan amplio. Por ello, esta tesis se centra en aportar contribuciones en entornos eMBB y URLLC, además de proponer soluciones a comunicaciones que se espera que vayan a ser relevantes en 6G.

En primer lugar, se ha propuesto el uso de NOMA como mecanismo que garantice la transmisión de contenido broadcast en aplicaciones eMBB. Para ello se ha definido la arquitectura necesaria y se ha construido un prototipo en software. Además del contenido broadcast, en las redes inalámbricas existen un amplio volumen de contenido unicast, y por eso, se ha diseñado un sistema de convergencia de los dos servicios para que puedan ser distribuidos al mismo tiempo. Posteriormente, se han diseñado diferentes esquemas de RRM basados en NOMA, donde también se ha gestionado dicha convergencia. Por último, se ha aplicado el conocimiento obtenido a casos de uso más específicos, como son las técnicas de agrupamiento de usuarios y las comunicaciones inalámbricas en la banda de frecuencias milimétricas.

En cuanto a URLLC, la ganancia que ofrecen los servicios basados en NOMA se ha orientado a mejorar diferentes parámetros, entre otros, la fiabilidad, la capacidad o la latencia. En un primer trabajo, se ha diseñado un prototipo de transceptor Wi-Fi basado en NOMA para aplicaciones industriales, ya que a día de hoy la gran mayoría de las aplicaciones industriales utiliza sus redes Wi-Fi. Asimismo, con el fin de aumentar la ganancia en fiabilidad se han estudiado e implementado diferentes esquemas de retransmisiones, en los cuales destacan los esquemas de diversidad espacial. Finalmente, también se ha estudiado la influencia de utilizar NOMA en los esquemas RRM, y se ha determinado que mejoran el rendimiento en comparación con las técnicas ortogonales, especialmente cuando los requisitos de la aplicación y de la red son más exigentes.

Por último, se ha contribuido en el ámbito de las comunicaciones full-duplex ya que se espera que vayan a tener gran relevancia en los futuros estándares de comunicación debido a su considerable incremento en la eficiencia espectral. En este caso, se ha diseñado un sistema que integra en la misma banda de frecuencia del contenido broadcast la señal de distribución. Este esquema está basado en el estándar de televisión digital estadounidense (ATSC 3.0) y utiliza LDM, una técnica NOMA específica, como mecanismo de multiplexación entre el contenido tradicional y la señal de distribución. Igualmente, a modo de evolución del sistema, se ha diseñado una arquitectura para interconectar los transmisores encargados de distribuir la señal de televisión. Por último, se han identificado los retos más relevantes asociados a esta contribución y se han planteado las soluciones que se probarán a corto plazo.

Esker onak

Hiru urte igaro dira doktoretza hasi nintzenetik. Orain, etapa hau ixteko unea da eta azken lerro hauek eskaini behar dizkiot denbora horretan lagundu didan jende guztiari.

Lehenik eta behin, eskerrak eman nahi dizkiet Pablori eta Joni, ikerketa munduan sartu baininduten. Gaur nagoen lekuan egotearen errua dute. Pablo, eskerrik asko aukera hau eskaintzeagatik eta nigan jarritako konfiantzagatik. Jon, mila esker urte hauetan erakutsi didazun guztiagatik eta lehenengo egunetik eskaini didazun adiskidetasunagatik.

Gainera, eskerrak eman nahi dizkiet laborategiko nire kideei, haiekin lan egin baitut denbora honetan zehar, eta haiekin partekatu baititut arrakastak eta porrotak. Marta, eskerrik asko eman dizkidazun aholku guztiengatik, etapa honetan argitu dizkidazun zalantzengatik eta bulegoko orduak atseginagoak egiteagatik. Eskerrik asko, Lorenzo, oraindik bidaiatzeko aukera zegoenean pasa ditugun une onengatik eta etorriko direnengatik. Iñigo eta Rufino, doktoretza hasi berri duzuenok, animo eta gozatu etapa honetaz, badakit primeran egingo duzuela! "Txispas"-ei (Mikel, Leire, JonGo eta Alex), oraindik ez zait oso argi geratzen zer egiten duzuen, baina plazer handia da zuekin kafearen uneak eta lanetik kanpo izaten ditugun mota guztietako elkarrizketak partekatzea. Bea, TSRn ezagutu nuen lehen pertsonetako bat izan zinen eta zurekin hitz egitea oso erraza egin zait beti. Eskerrik asko Iker, lanean zein lanetik kanpo partekatzen ditugun barre-une eta zoramen guztiengatik. Teresa, mila esker zure laguntzagatik eta prestutasunagatik, gure lana askoz errazagoa izatea egiten duzu. Eskerrik asko Aritz eta Aitorri, zuen lanarekin lagundu diguzuen guztiagatik eta erakutsi duzuen ikasteko gogoagatik. Eskerrik asko, baita ere, TSR taldeko gainerako irakasleei, guztiengandik gauzak ikasi ahal izan ditudalako eta bidea askoz errazagoa egin duzuelako.

Era berean, CRCko kideak gogoratu nahi nituzke, han egon nintzen denboran etxean bezala sentiarazi nindutenak. Eskerrik asko Yiyan, nigan jarritako konfiantza guztiagatik, zugandik ikasi ahal izan dudun guztiagatik eta lanetik kanpo hainbeste leku erakusteagatik. Wei, eskerrik asko nire zain egoteagatik eta hain gustura sentiarazteagatik. Eta Liang, eskerrik asko zure ezagutzak nirekin partekatzeagatik eta uneoro laguntzeagatik. Kanadan berriz elkar ikustea espero dut.

Ikerlaneko lankide ohiei esker, han ikertzaile gisa trebatzen hasi nintzelako, eta oso oroitzapen ona dudalako. Berezi, eskerrak eman nahi nizkioke Iñakiri nirekin izan zuen pazientziagatik eta berari esker profesionalki hazi nintzen guztiagatik. Oscarrekin solasaldi luze-luzeak egin ditut hainbat kontzeptu teknologikori buruz (eta beste batzuk ez

teknologikoei buruz), eta pozten naiz gaur egun elkarrekin lanean jarraitu ahal izateaz. Cristinari esker ere, autoz ordu asko eman nituen berarekin, eta askoz ere atseginago egin nituen Arrasatera egindako bidaiak.

Azkenik, nire familiari eskerrak eman nahi nizkioke. Gurasoei eta arrebari, hazten ikusi nautelako eta gaur egun definitzen nauten balioak transmititu dizkidatelako. Patxiri eta Gemmari, hasieratik seme bat bezala tratatzeagatik. Baina batez ere zuri esker, Nagore. Etapa honetan izan zaren guztia eta nire bizitzan zarena hitzez adieraztea ezinezkoa da. Eskerrik asko zaren bezalakoa izateagatik eta beti hor egoteagatik. Eskerrik asko guztiagatik.

Gaien zerrenda

Laburpena	v
Abstract	vii
Resumen	ix
Esker onak	xi
Irudien zerrenda	xv
Taulen zerrenda	xvii
1 Tesiaren sintesia	1
1.1 Ikuspegi orokorra	1
1.1.1 Sarrera	1
1.1.2 Motibazioa	7
1.1.3 Dokumentuaren egitura	8
1.2 Esparru teorikoa. Artearen egoera	9
1.2.1 NOMA	10
1.2.1.1 Kontzeptu orokorrak	10
1.2.1.2 NOMA tekniken taxonomia	13
1.2.1.3 Inplementazio erronkak	16
1.2.1.4 NOMAren aplikazioak	18
1.2.1.5 Garatzeke dauden gaiak	26
1.2.2 RRM	29
1.2.2.1 Kontzeptu orokorrak	29
1.2.2.2 RRM tekniken taxonomia	32
1.2.2.3 Optimizazio estrategiak	35
1.2.2.4 Garatzeke dauden gaiak	41
1.3 Hipotesiak eta helburuak	44
1.3.1 Helburuak	44
1.3.2 Ekarpenak	46
1.4 Laburpena eta emaitzak	50
1.4.1 Broadcasterako NOMA eMBBn	50
1.4.2 Aplikazio kritikoetarako NOMA URLLCn	52

1.4.3	Full-duplex NOMA 6G sareetarako	54
1.5	Bibliografia	56
2	Ondorioak eta etorkizuneko lanak	75
2.1	Ondorioak	75
2.2	Etorkizuneko lanak	78
3	Publikatutako edo onartutako artikuluak	81
3.1	1. ekarpenarekin erlazionatutako artikuluak	81
3.1.1	Konferentzia-artikulua (K1)	81
3.1.2	Aldizkari-artikulua (A1)	88
3.1.3	Konferentzia-artikulua (K2)	101
3.1.4	Aldizkari-artikulua (A2)	108
3.1.5	Aldizkari-artikulua (A3)	122
3.2	2. ekarpenarekin erlazionatutako artikuluak	134
3.2.1	Konferentzia-artikulua (K3)	134
3.2.2	Aldizkari-artikulua (A4)	141
3.2.3	Konferentzia-artikulua (K4)	154
3.2.4	Aldizkari-artikulua (A5)	163
3.2.5	Aldizkari-artikulua (A6)	178
3.2.6	Aldizkari-artikulua (A7)	198
3.3	3. ekarpenarekin erlazionatutako artikuluak	203
3.3.1	Konferentzia-artikulua (K5)	203
3.3.2	Aldizkari-artikulua (A8)	210
3.3.3	Aldizkari-artikulua (A9)	226
A	Beste argitalpen batzuk	239
A.1	Nazioarteko aldizkariak	239
A.2	Nazioarteko konferentziak	240
A.3	Liburu kapituluak	247
B	Curriculum	249
C	Glosarioa	251

Irudien zerrenda

1.1	ITU-R M. 2083-0 txostenean aurkeztutako erabilera-kasu eta aplikazioen sailkapena [7]	2
1.2	NOMA eta RRM tekniken erabilera konbinatua aplikatzeko agertoki nagusiak	8
1.3	Tesi honi lotutako lan-arlo nagusiak	9
1.4	OMA eta NOMA tekniken zerbitzuen ahalmenen alderaketa harrera-baldintza desberdinetarako	12
1.5	NOMA teknika adierazgarrienen sailkapena	13
1.6	NOMA tekniken inplementazio-erronka adierazgarrienen sailkapena	16
1.7	NOMAREN etorkizuneko ikerketa-arloak alor ezberdinetan antolatuta	27
1.8	Irizpide ezberdinen arabera RRM tekniken sailkapena	32
1.9	RRM eskemen etorkizuneko ikerketa-lerroak	42
1.10	Tesiaren helburuekin lotutako erronka nagusiak.	45
1.11	Tesiaren ekarpenen irudikapena.	47

Taulen zerrenda

1.1	ITU-R M. 2083-0-n aurkeztutako sailkapenaren erabilera- kasu bakoitzeko eskakizun minimoak [8]	3
1.2	Efizientzia espektrala hobetzeko teknika adieragarrienen laburpena	5
1.3	6Grako funtsezko teknologia gaitzaileen deskribapena . . .	6
1.4	Komunikazio mugikorretarako erabilitako OMA tekniken laburpena	11
1.5	3GPPk NOMA eskemei buruz egindako azterlanen laburpena	21
1.6	Aplikazio ezberdinetarako NOMAri buruzko ekarpen nagusien laburpena	23
1.7	Diseinu-irizpide ezberdinen arabera RRM tekniken kate- gorien laburpena	36
1.8	RRM optimizazio-metrika ezberdinekin aztertutako lanen laburpena	41

1. Kapituluia

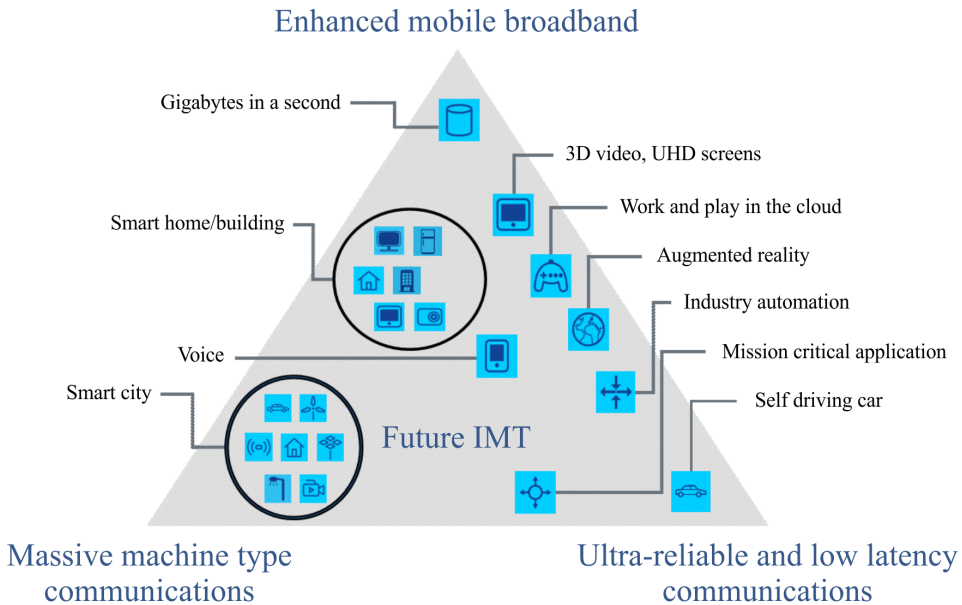
Tesiaren sintesia

1.1 Ikuspegi orokorra

1.1.1 Sarrera

Hamarkada honetako erronka teknologiko garrantzitsuenetako bat sarean zirkulatzen ari den trafiko-kopuruaren hazkunde azkarraren kudeaketa eraginkorra da. Izan ere, Ciscok datu mugikorren trafiko globala, 2021 urtean zehar, hileko 49 Exabytetan handituko dela uste du [1]. Ericssonek, bestalde, 2018tik 2024ra bitartean trafiko mugikorra %30 haziko dela aurreikusi du, eta hazkunde horren zatirik handiena bideo zerbitzuetatik etorriko da [2]. Munduan gertatzen ari den hazkunde esponentzialaren arrazoi bat konektatutako gailuen kopurua handitzea da. Zehazki, 2030erako, 50 mila milioi gailu sare globalera konektatuta egotea espero da [3]; horietatik 1,4 mila milioi telefono adimendunak eta tabletak dira [4]. Bestalde, datuen gehikuntza masiboaren beste arrazoi bat multimedia-edukiaren eskaria handitzea da, hala nola bideo-streaming-a edo Errealitate Areagotuan (EA) eta Errealitate Birtualean (EB) oinarritutako zerbitzuak, erabiltzaile bakoitzeko 100 Mbps-ra arte eskatuko dezaketanak [5]. Gainera, espero da IP bideo-zerbitzuen eskari globala laukoiztu egingo dela 2017tik 2022ra artean [6].

2015ean, International Telecommunication Union erakundeko irrati komunikazioen sektoreak (ITU-R) garatzen ari diren 5G teknologiek etorkizuneko sareetan izango duten eginkizuna aztertzeke talde bat proposatu zuen. Talde hau International Mobile Telecommunications-2020 (IMT-2020) izena du eta, besteak beste, gaur egungo eta etorkizuneko aplikazioak sailkatu zituen hiru erabilera-kasutan: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), eta massive Machine Type Communications (mMTC) [7]. 1.1 irudian, familia bakoitzari egokitzen zaizkion erabilera-kasuen eta aplikazioen laburpena agertzen da. Alde batetik, eMBBren helburua



IRUDIA 1.1: ITU-R M. 2083-0 txostenean aurkeztutako erabilera-kasu eta aplikazioen sailkapena [7]

etenik gabe datuen abiadura handiko estaldura ematea da, mugikortasun handiko agertokiak barne. Kasu honetan erabiltzen diren aplikazioetako batzuk 3D bideoak, 4k/8k edukia eta EA/EB zerbitzuak dira. Gero, mMTC Gauzen Internet edo Internet of Things (IoT) kontzeptuarekin lotutako saretarako definitzen da, non energia kontsumo txikia eta nodo kopuru handi baterako datu abiadura txikiak behar diren. mMTC aplikazioen adibide ezagun batzuk hiri adimendunak eta haririk gabeko sentsoare sarea dira. Azkenik, URLLC segurtasun eta aplikazio kritikoetara bideratuta dago, non aplikazio-inguruneak oso adierazgarriak diren, hala nola automatizazio industrialak edo auto autonomoak.

Erabilera kasu bakoitzaren filosofia ezberdinak direla eta, erabilera kasu bakoitzaren implementazioarekin erlaziozko baldintzak ezberdinak dira. 1.1 taulak parametro garrantzitsuenen eta horien erreferentzia-balioen laburpen bat erakusten du, [8]-n ezarritakoaren arabera. Ikus daitekeenez, erabilera-kasu bakoitzerako parametro kritikoak desberdinak dira. Parametroa erabilera-kasuaren adierazgarria ez diren kasuak gidoi baten bidez adierazi dira. Adibidez, eMBBren errendimenduaren funtsezko adierazle edo key performance indicator (KPI) adierazgarrienak datuen abiadurarekin lotuta daude, hala nola datuen abiadura maximoarekin, non 20 Gbps eta 10 Gbps bermatu behar diren beharrezko eta goranzko loturarako, hurrenez hurren.

TAULA 1.1: ITU-R M. 2083-0-n aurkeztutako sailkapenaren erabilera-kasu bakoitzeko eskakizun minimoak [8]

Parametroa	Balioa		
	eMBB	URLLC	mMTC
Datu tasa maximoa	20 Gpbs beheranzko loturan 10 Gpbs goranzko loturan	-	-
Efizientzia espektral maximoa	30 bps/Hz beheranzko loturan 10 bps/Hz goranzko loturan	-	-
Erabiltzaileak jasotako datu tasa	100 Mpbs beheranzko loturan 50 Mpbs goranzko loturan	-	-
Trafiko bolumena areako	10 Mbit/s/m ²	-	-
Latentzia erabiltzaile-planoan	4 ms	1 ms	-
Latentzia kontrol-planoan	20 ms	20 ms	-
Konexio-dentsitatea	-	-	1 000 000 gailu km ² -ko
Fidagarritasuna	-	10 ⁻⁵	-
Mugikortasuna	Kasuaren araberakoa 500 km/h-ra arte	-	-
Mugikortasunaren etenaldi denbora	0 ms	0 ms	-
Banda-zabalera	Gutxienez 100 MHz eta GHz batera arte 6 GHz-tik gorako bandetan		

Ondoren, URLLCren betekizun nagusiak zerbitzu sendoak (hau da, errore-tasa 10^{-5} -tik beherakoa) eta latentzia baxuko zerbitzuak (hau da, milisegundo batetik beherakoa erabiltzaile-planoan) ematera bideratuta daude. Azkenik, mMTCri dagokionez, alderdirik garrantzitsuena konexio dentsitatea da, km²-ko milioi bat gailu inguru espero dena.

5G lehen aipatutako erabilera-kasu guztiak estaltzeko sortu zen. 5Gren ezaugarri nabarmenenetako bat bere geruza fisiko (PHY) malgua da, erabilera kasu desberdinen beharrak betetzen dituena [9]. Zehazki, 5Gren lehen bertsioa (hau da, Rel-15) 2018an argitaratu zen [10]-n. Bertsio hau eMBBn zentratu zen eta New Radio (NR) teknologiak barne hartu zituen. Ondoren, Rel-16 gainerako erabilera-kasuak estaltzera (hau da, URLLC eta mMTC) bideratu zen, baita beste alderdi batzuk ere, hala nola Vehicle-to-Everything (V2X) eedta 3GPP ez diren sistemekin batera existitzea [11]. Bestalde, Rel-17 eta ondorengo bertsioek (azken bertsioa Rel-20 izango da) 5G sarea komunikazio-tresna eraginkorrez hornitzea espero da. Hona hemen adibide garrantzitsu batzuk: haririk gabeko eta kable bidezko konbergentzia, multicast eta broadcast arkitekturak, hurbiltasun-zerbitzuak, sarbide anitzeko ertzeko informatika eta sareen automatizazioa [12].

5Gk teknologien, aplikazioen eta aukeren ekosistema oso bat sortu du bere inguruan, haririk gabeko komunikazioen etorkizuna gidatu nahi duena. 5G sareek aplikazio, teknologia eta estandar horiek guztiak baliatzea haririk gabeko komunikazioetarako estandar bakar bat baino askoz gehiago bihurtzeko espero da. Epe ertainera, 5G ia erabilera-kasu guztietara egokitu daitekeen ekosistema teknologiko oso bat izango da. Izan ere, ikuspegi hori izango du 5G terminoak doktoretza tesi honetan.

5Gk ekartzea espero den onura teknologikoetako bat hari gabeko komunikazio-sistemen konbergentzia da [13]. Adibidez, estaldura hobetzeko, satellite bidezko komunikazio sistemak 5G ekosisteman integratzea proposatu da [14], edo sare heterogeneoen konbergentzia, hala nola broadcast, Wi-Fi eta sare zelularren arteko zerbitzuak [15], edo zerbitzu finkoak eta mugikorak [16].

Hala ere, 5G oraindik inplementazioaren hasierako etapetan dagoen arren, eta epe labur/ertainean inplementazio masiborik espero ez den arren, muga batzuk antzeman dira. Literatura berrienaren arabera, muga nabarmenetako batzuk honako hauek dira: sistemak ingurune ultra dentsuetan duen estaldura, guztiaren interkonexio falta (edo interconnection of everything, IoE) eta aplikazio industrial kritikoetarako zero-latentzia duten sistemak [17]. Hori dela eta, teknologiaren bilakaera bi norabidetan bideratuta egongo da ziurrenik: 1) existitzen diren tekniketarik abiatuta, zerbitzuaren kalitatea hobetuko duten espektroaren efizientzia hobetzeko teknikak diseinatu eta balioztatu, eta 2) 6Gk bete behar dituen baldintzak eta erabilera-kasuak zehaztu.

Espektroaren eraginkortasunari eta malgutasunari dagokienez, arlo honek egungo 5G ekosisteman oinarritutako soluzio inplementagarrien ikerketa estaltzen du. Horretarako, ezaugarri ezberdinak dituzten teknikak erabil daitezke. Zehazki, 1.2 taulak hautagai garrantzitsuenen laburpena erakusten du. Bereziki, T1 eta T7 5Gren etorkizuneko bertsioekin estuki lotutako bi teknika dira. mmWave-ren erabilerak eskuragarri dagoen banda-zabalera nabarmen handitzen du, eta transmisio-/harrera-antena ugari erabiltzeko egoera ezin hobea planteatzen du. Sarbide anizkoitz ez-ortogonaletan oinarritutako teknikak (Non-Orthogonal Multiple Access, NOMA) espektroaren eraginkortasuna hobetzeko etorkizun handiko hautagaitzat hartzen dira. Izan ere, transmititutako potentzia zatitzean erabiltzaile kopuru handi bati aldi berean zerbitzatzeko aukera eskaintzen baitute. Beste teknika egoki bat transmititutako kapazitatea areagotuko luketen ordena altuko konstelazioak erabiltzea da. Teknika hori beste komunikazio-estandar ezagun batzuetan estandarizatzen ari da, hala nola Wi-Fi edo irrati-difusiorako teknologietan. Bestalde, sarearen zenbait alderdiren erabilera eraginkorra eta diseinua kritikoak izan litezke espektroaren eraginkortasunerako, T4 eta T5, esaterako, kudeaketa-alderdi desberdinak adierazten dituztenak. Nabarmentzekoa da T4 VNF eta SDN sistema birtualizatuen diseinu adimendunean oinarritzen den bitartean, T5 (Irrati-baliabideen kudeaketa edo Radio Resource Management, RRM) eskuragarri dauden irrati-baliabideen kudeaketa eraginkorrera bideratuta dagoela. Gainera, kodetze-sistemak oso garrantzitsuak izan dira komunikazioaren sendotasuna hobetzeko, eta egungo kodifikazio-eskemak Shannon-en mugatik oso gertu daude.

TAULA 1.2: Efizientzia espektrala hobetzeko teknika adieragarrienen laburpena

ID	Teknika	Deskribapena	Erreferentziak
T1	mmWave bandak	mmWave banden erabilerari esker, banda-zabalera handiagoak erabil daitezke, ahalmen handiagoko zerbitzuak eskaintzeko	[18] [19]
T2	NOMA	Energia-banaketa aplikatzean, irrati-baliabide beraren barruan erabiltzaile asko zerbitzatzea posible da	[20] [21]
T3	Konstelazio masiboak	256 sinbolo baino gehiagoko konstelazioen eskemak	[22] [23]
T4	Sarearen kudeaketa adimentsua	Sare banatuaren diseinua Virtualized Network Function (VNF) eta Software Defined Networking (SDN)-n oinarrituta	[24] [25]
T5	RRM	Irrati-baliabideak esleitzeko etapa optimizatzea	[26] [27]
T6	Kodetze aurreratua	Kodetze teknika modernoak Shannon-en muga hurbiltzen ari dira. Adibidez, LDPC, turbo kodeak edo kode polarrak	[28] [29] [30]
T7	MIMO masiboa	Antena ugari dituzten komunikazio-sistemak. 128 x 128 arteko probak	[31] [32]
T8	Irrati kognitiboa	Gutxiegi erabiltzen diren maiztasun-bandak dinamikoki alokatzen ditu	[33] [34]

Azken teknika, T8 alegia, azpierzaitako frekuentzia-bandak hautematera eta beste aplikazio batzuetarako erabilera kudeatzera bideratuta dago, komunikazio-gaitasuna hobetzeko eta sarearen pilaketa murrizteko. Azkenik, aipatzekoa da zerrendatutako teknikak OSI (Open Systems Interconnection) arkitekturaren geruza ezberdinekin lotu daitezkeela, eta horrek komunikazioaren eraginkortasuna hobetu dezake hainbat mailatan. Zehazki, T2, T3, T6 eta T7 PHY teknikak dira, eta gainerakoak goragoko geruzetara bideratuta daude, hala nola sare- eta garraio-geruzak.

Aldiz, bigarren ikerketa-biderako (6Grako bidea), 6Gren deskribapen argirik ez dagoen arren, erabilera kasu aplikagarrien eremua zabaltzeko gaitasun hobetuak izatea espero da. Izan ere, orain arteko lanek 6Gren erabilera aplikazio berrietarako aurreikusten dute, hala nola, [35]-n, non komunikazio holografikoak proposatzen diren; [36]-n, non ikasketa automatikoaren (Machine Learning, ML) eta konputazio kuantikoaren (Quantum Computing, QC) konbinazioa gertu dagoen azpimarratzen den edo [37]-n, non super IoT eta Adimen Artifizialeko (AA) iradoki dituzte. 6Gren beste hobekuntza esparru bat latentzia baxuko eta komunikazio masibo ultra fidagarri gisa (hau da, massive ultra-reliable low latency communications, mURLLC) erabiltzen diren kasuen konbinazioa garatzea da [38, 39]. Proposatutako eskakizun berriak eta erabilera-kasuak betetzeko, teknologia disruptibo multzo bat definitu beharko da, 6Gn integratzeko. 1.3 taulak teknologien laburpen bat erakusten du,

TAULA 1.3: 6Grako funtsezko teknologia gaitzaileen deskribapena

ID	Teknologia	Deskribapena	Erref.
G1	THz komunikazioak	Frekuentzia-bandak mmWave gainera. Banda-zabalera eta ahalmen handiagoak	[40]
G2	Visible Light Communications (VLC)	RF transmisio-sistemak argia igortzen duten mekanismoekin osatzea	[41]
G3	Energia transferentzia eta sorkuntza	Energia-iturri berriak eta energia-eraginkortasuna hobetzeko kudeaketa	[42]
G4	Full-duplex komunikazioak	Seinaleak jaso transmititu bitartean. Beharrezkoa da interferentzien ezeztatzea	[43]
G5	Sarean oinarritutako kokapena	RF seinaleak erabiltzea erabiltzaileak/gailuak kokatzeko eta mapeatzeko	[44]
G6	3D sare arkitekturak	Lurrekoak ez diren transmisioak osagarri gisa erabili. Adibidez, droneak edo sateliteak	[45]
G7	Backhaul soluzio efizienteak	Backhaul eraginkorra behar da sarerako sARBIDEAREN IGOERA KONPENSATZECO	[46]
G8	AAAn oinarritutako ikasketa	Bildutako informazioaren balioa maximizatzeko AA teknikak	[47]

ustez 6Gn funtsezko teknologia gaitzaile direnak. mmWave bandetan komunikazioak ezartzeko urrats zuzena da G1. Hala ere, espektra kudeatzeko eta uhin milimetrikoen bandetan sareak planifikatzeko erronkek eta ekipo ezak ikerketa-ahalegin handiagoa eskatzen dute. Hortaz, VLC estaldura hobetua edo itzulera-transmisioa emateko etorkizun handiko osagarritzat hartzen da. Kontuan izanik energetikoki egokiak diren komunikazioak behar direla, energia-iturrien kudeaketa eta bilketa zuzena etorkizuneko sentore-sareen gai garrantzitsutzat jotzen dira. G4ri dagokionez, full-duplex komunikazioek nabarmen hobetu dezakete sarearen eraginkortasuna aldi berean transmititu eta jasotzen baitute. Hala ere, autointerferentziaren erronkak alde aurretik gaitu behar dira. Horrez gain, sareetan oinarritutako kokapena funtsezkoa da industria-inguruneetan, langileen etengabeko kokapena ezinbestekoa baita segurtasuna bermatzeko. 6Gn soluzio berriak aurreikusten dira transmititutako/jasotako RF seinaleetan oinarrituta. G6k lurrekoak ez diren sareen integrazioa aldarrikatzen du (adibidez, droneak, globoak edo sateliteak) lurreko sareen plangintzan. Ondoren, sarera konektatzeko eskaeretan espero den igoera esponentziala dela eta, backhaul seinalea eraginkortasunez kudeatu eta transmititu behar da. Azkenik, ML bezalako AA teknikak erabiltzea espero da sarean bildutako datu guztiak administratzeko eta datu horietatik abiatuta ikasteko, sarea adimentsua izan dadin.

Oro har, bi ikerketa-bide horiek denbora eta ondorio desberdinak dituztela nabarmendu behar da. Alde batetik, 5Grako espektraoren

eraginkortasun-teknikak egungo sistemetan sare-errendimendua ematen duten soluzioen multzoa dira. Bestalde, 6Gn oinarritutako soluzioak epe luzerako garapenak dira, eta ezin dira epe labur edo ertainean inplementatu, baina errendimendu-irabazi izugarriak eman ditzakete. Beraz, etorkizuneko ikerketa-ildoek proposatutako bi bideak bete behar dituzte, haririk gabeko komunikazio-sistemen orainari eta etorkizunari irtenbideak emateko.

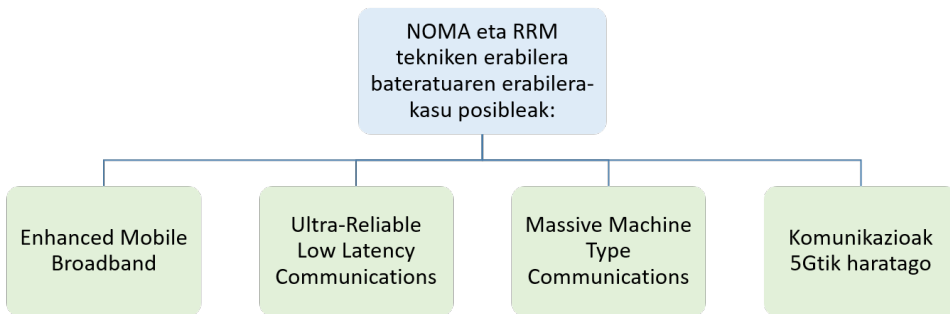
1.1.2 Motibazioa

Aurreko atalean deskribatzen den bezala, egungo komunikazio-sistemen espektroaren eraginkortasuna hobetzeko premia dago, erabilera-kasu desafiatsuak diren aurre egiteko. Gaur egungo komunikazio-sistematan espektroaren eraginkortasuna hobetzera bideratuta dago tesi hau. Zehazki, 1.2 taulan espektroaren eraginkortasuna hobetzeko agertzen diren tekniken zerrenda erreferentziatzen hartuta, tesi honek T2 (hau da, NOMA) eta T5 (hau da, RRM) teknikak 5G ekosistemaren teknologiek konbinatuta erabiltzea proposatzen du.

Tesiaren norabidea bermatzeko lehen arrazoia bi teknologia horiek OSI geruza desberdinetan oinarrituta daudela da, eta horrek espektro-eraginkortasuna bi ikuspegi desberdinetatik hobetzea ahalbidetzen du. Ikerketa bide hau aukeratzeko beste arrazoi bat PHY diseinuen hobekuntza tarte txikian datza, egungo komunikazio estandarrek Shannon-en mugatik oso gertu funtzionatzen baitute. Beraz, espektroaren eraginkortasunerako teknika berriak proposatu behar dira, PHY geruzan oinarritutakoak bakarrik ez direnak.

Epe laburrean garrantzitsuak izan daitezkeen erabilera-kasuak konbentzientzia hartuta, eta [7]-n eginako sailkapena erreferentziatzen hartuta, lau agertoki posible definitu dira, non 5Gren emaitzak eta etorkizuneko 6G sareak nabarmen hobetu daitezkeen NOMA eta RRM konbinazioa aplikatuz eta probatuz. Egoera posibleen laburpen bat 1.2 irudian erakusten da, eta horietako bakoitza jarraian zehazten da:

- Enhanced Mobile Broadband: NOMA eta RRM eMBBn erabil litezke espektroa era efizienteagoan erabiltzeko, sarearen errendimendu orokorra handitzeko edo zerbitzuaren kalitatea hobetzeko dentsitate handiko inguruneetan.
- Ultra-Reliable Low Latency Communications: proposatutako tekniken erabilera konbinatuarekin lortutako espektroaren efizientziaren hobekuntza komunikazioen fidagarritasuna hobetzeko erabil liteke, zerbitzu sendoagoak eskainiz. Horrela, baldintza zorrotzak gertuago egongo lirateke.



IRUDIA 1.2: NOMA eta RRM tekniken erabilera konbinatua aplikatzeko agertoki nagusiak

- Massive Machine Type Communications: mMTC inguruneen zailtasun nagusia sarerako sarbidea eta sare horiek osatzen dituzten gailu askoren zerbitzua aldi berean bermatzea da. NOMA eta RRM batera erabiltzeak malgutasun handiagoa eman lezake zerbitzuaren diseinuan, eta, ondorioz, zerbitzatutako gailu kopurua handiagotu.
- Komunikazioak 5Gtik haratago: etorkizuneko komunikazio estandarrek oraindik ez daude guztiz definituta. Aitzitik, gaur egungo komunikazio estandarren ahuleziak eta baldintza zorrotzak direla eta kontuan hartu ezin diren erabilera-kasuak errealitate dira. Beraz, NOMA eta RRM tekniken konbinazioaren bidez lortutako espektroaren efizientziaren hobekuntza gaur egun erabiltzen diren kasuak egungo komunikazio estandarren irismenetik kanpo jasatera bidera liteke.

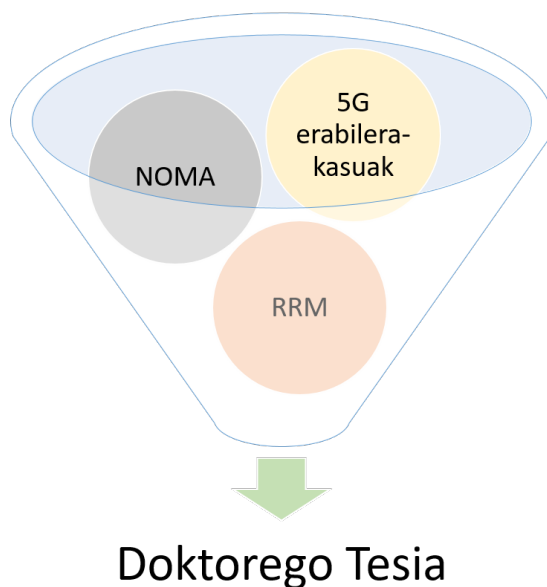
1.1.3 Dokumentuaren egitura

Tesi hau hiru kapitulutan antolatuta dago. Kapitulu bakoitzaren edukia honela banatzen da:

1. kapitulua: kapitulu honek tesiaren sintesia aurkezten du. Lehenik, tesi honen aurrekariak eta motibazioen deskribapena jasotzen dituen deskribapen orokor bat aurkezten da. Gero, lanaren testuinguru teknikoa deskribatzen da, gaiarekin lotutako azterlanen literatura zientifikoaren berrikuspenetik abiatuta. Ondoren, hipotesiak eta helburuak deskribatzen dira. Azkenik, hurrengo atalak ekarpen bakoitzean lortutako emaitzak aztertzen ditu, eta bibliografiak, berriz, kapitulua ixten du.

2. kapitulua: azken kapitulu honetan lanetik ateratako ondorio nagusien laburpena eta ekarpen bakoitzari lotutako etorkizuneko ildoen deskribapena aurkezten dira.

3. kapitulua: kapitulu honek ekarpen bakoitzarekin lotutako



IRUDIA 1.3: Tesi honi lotutako lan-arlo nagusiak

artikuluak biltzen ditu. Horrez gain, lan bakoitzaren kalitate-adierazle nagusiak ematen dira.

Azkenik, eranskinen atalak egilearen beste argitalpen batzuk, curriculum eta glosarioa zerrendatzen ditu.

1.2 Esparru teorikoa. Artearen egoera

Aurreko atalean erakusten den bezala, aplikazio berrien eskaria handitzea eta datuen abiadura handiagoak haztea egungo errealitatea da. Horregatik, ikerketa-komunitateak espektroaren erabilera hobetzeko teknikarik berritzaileenak eman behar dizkie komunikazio-sistemei. Tesiaren helburua espektroa era eraginkorrean erabiltzen dituzten teknika berriak diseinatzea eta probatzea da. Lan honen testuinguru teknologikoa behar bezala ulertzeko, 1.3 irudia har daiteke erreferentziatzat, non tesi hau hiru zutabetan oinarritzen dela ikus daitekeen: NOMA, RRM eta 5Gren erabilera-kasuak.

Alde batetik, NOMAn oinarritutako teknikak etorkizun handiko multiplexazio-teknologiatzat hartzen dira, teknika ortogonal tradizionalekin alderatuta espektro-eraginkortasuna nabarmen hobetzen dutelako. Beraz, haririk gabeko komunikazioen egungo estandarren bilakaera nagusietako bat izan daitezke. 1.2.1 sekzioak NOMA tekniken

deskribapen orokorra aurkezten du, baita arlo horretan aurkeztutako ekarpen nagusien analisisa ere.

Bestalde, erronka-aplikazioak eta baliabide-eskatzaileak ugaritu direnez, eskuragarri dauden baliabide irrati elektrikoen eskasia nabarmena da. Hortaz, baliabideen kudeaketa eta erabilera optimizatua funtsezkoa da egungo komunikazio-sistemetan. Gainera, OSI arkitekturako geruza desberdinetako tekniken konbinazioak, NOMA eta RRM, espektroraginkortasuna maila gorenetara eraman dezake. 1.2.2 sekzioaren ardatza RRM tekniken azalpen zehatza ematea eta egungo literaturaren ekarpen garrantzitsuenak aztertzea da.

Azkenik, nabarmendu behar da, edozein teknologia garatu aurretik, zein erabilera-kasutan aplikatuko den jakin behar dela, teknologiak izan behar dituen ezaugarriak eta betebeharrak ezagutzeko. Kasu honetan, 5Gren barruko aplikazio batzuk ebaluatzen dira, eta 5G ekosistematik kanpoko erabilera kasuak ere, haririk gabeko etorkizuneko komunikazioetan garrantzitsuak izatea espero direnak. 5Gtik haratagoko erabilera-kasuen azterketa 1.1.1 kapituluan aurkeztu da.

Hurrengo azpiataletan, doktoretza honetan batera ebaluatu diren eraginkortasun espektraleko bi tekniken (NOMA eta RRM) tutorial xehatua eta azterketa-analisisa aurkezten dira.

1.2.1 NOMA

1.2.1.1 Kontzeptu orokorrak

Tradizionalki, sarbide anizkoitz ortogonaleko (Orthogonal Multiple Access, OMA) teknikak sarritan erabili izan dira banda zabaleko komunikazioetan zerbitzuak eta erabiltzaileak multiplexatzeko. OMA teknikek denbora, maiztasuna eta kodea bezalako baliabideak esleitzen dizkiote erabiltzaile bakoitzari. Beraz, ez dago interferentziarik erabiltzaileen artean, baina onartutako gehienezko erabiltzaile kopurua mugatua da, baliabideen esleipen eskusiboagatik. 1.4 taulak, OMA teknikek azken hamarkadetan izan duten bilakaeraren eta komunikazio mugikorreko estandarren laburpena erakusten du. Inplementatutako lehen OMA teknika frekuentzia banaketa bidezko sarbide anizkoitza (Frequency Division Multiple Access, FDMA) izan zen 1Gn. FDMA, erabiltzaile bakoitzak bere seinale propioa transmititzen du frekuentzia-banda batean, eta, beraz, hartzaileak erabiltzaile guztien seinaleak antzeman ditzake frekuentzia-kanala aldatuz. Gero, 2Gn, denbora banaketa bidezko sarbide anizkoitza (Time Division Multiple Access, TDMA) sartu zen. Kasu honetan, TDMA, erabiltzaile bakoitzari denbora-tarte eskusiboak esleitzen zaizkio, harreraren denbora-tarte egokiak entzunda erabiltzaile desberdinak bereizteko. 2000ko hamarkadan, 3G agertu

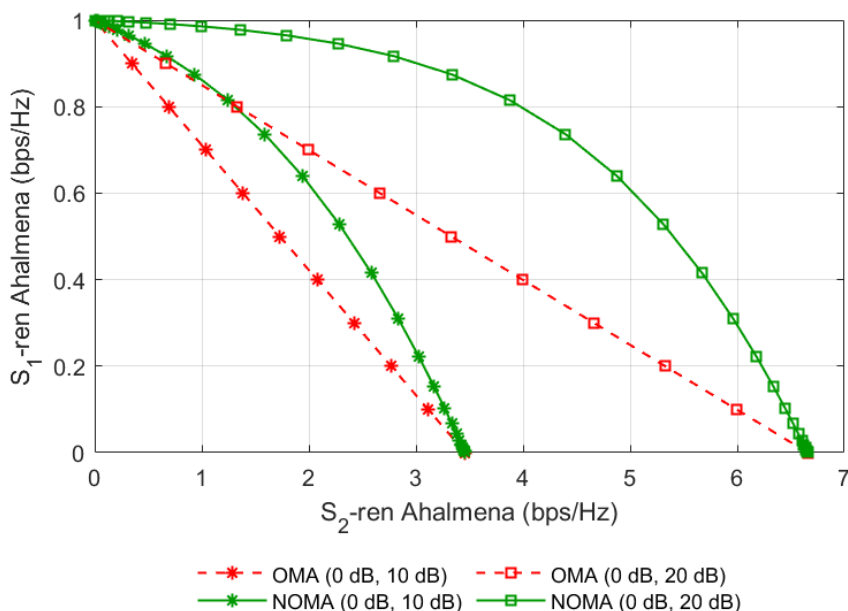
TAULA 1.4: Komunikazio mugikorretarako erabilitako OMA tekniken laburpena

Teknika	Belaunaldia	Hamarkada	Deskribapena
FDMA	1G	1980	Frekuentzia-banda eksklusiboak esleitzen zaizkio erabiltzaile bakoitzari
TDMA	2G	1990	Denbora-tarte eksklusiboak esleitzen zaizkio erabiltzaile bakoitzari
CDMA	3G	2000	Transmititutako informazioa hedapen sekuentzia ortogonalei esleitzen zaie
OFDMA	4G	2010	Esleipena denbora eta maiztasuna domeinuan egiten da

zenean, kontzeptu berri bat sartu zen: kode banaketa bidezko sarbide anizkoitza (Code Division Multiple Access, CDMA). Aurreko kasuetan ez bezala, erabiltzaileek denbora-frekuentzia baliabide berberak partekatzen dituzte, transmititutako seinalea hedapen ortogonaleko sekuentziei esleitzen zaien bitartean [48]. 3Gn erabilitako hedapen sekuentzia ezagunenetakoa bat Walsh-Hadamard [49] kodifikazio eskema izan zen. Azkenik, komunikazio mugikorren sistemetakoa OMA tekniken azken eboluzioa frekuentzia ortogonaleko banaketa bidezko sarbide anizkoitza (Orthogonal Frequency Division Multiple Access, OFDMA) izan zen. OFDMA, FDMA eta TDMA tekniken konbinaziotzat har liteke, baliabideak bi dimentsioko lauki batean esleitzen baitira (hau da, denbora eta maiztasuna) [50].

OMA tekniken onura nagusietako bat erabiltzaileen seinaleek ez dutela elkar oztopatzen da. Beraz, erabiltzaile bakoitzaren seinaleak konplexutasun txikiko detektagailuekin eskura daitezke. Hala ere, baliabide ortogonal kopuruak OMA tekniken bidez zerbitzatutako erabiltzaile kopurua mugatzen du. Zalantzarik gabe, efektu hori eragozpen garrantzitsua da 5G aplikazioetan kontuan hartzen diren komunikazio masiboetarako. Horregatik, NOMA OMA tekniken mugak gaindi ditzakeen teknologietako bat dela kontsideratzen da [51].

NOMA tekniken ezaugarri bereizgarri nagusia baliabide multidimensional berberak (hau da, denbora, maiztasuna edo kodea) erabiltzaile askori esleitzen dizkietela da. Beraz, kanalaren banda-zabalera osoa eta denboraren %100 erabiltzen da aldi berean hainbat zerbitzu emateko. Beraz, NOMA teknikek OMA teknikek baino erabiltzaile gehiagori eman diezaiekete zerbitzua, baliabide ez-ortogonalak esleitzeko sistema dela eta. Informazioaren teoriaren ikuspegitik, [52]-n egindako analisisa jarraituz, NOMAk espektroa hobeto aprobetxatzen du eta, beraz, espektro-efizientzia handiagoa du. 1.4 irudian, NOMA eta OMAREN arteko kanal-ahalmenaren alderaketa aurkezten da, non estazio base batera transmititutako zerbitzu pare bat erabiltzen diren. Seinale/zarata erlazioko (Signal-to-Noise Ratio, SNR) bi konbinazio desberdin hartu dira kontuan. Aipatzekoa da NOMAk OMA gainditzen duela kasu guztietan. Adibidez, 0 dB eta 10 dBko SNRak dituzten zerbitzuetan, 0,2 bps/Hz eta 0,5 bps/Hz-ko irabazia lor daiteke S1 eta S2rako, hurrenez hurren.

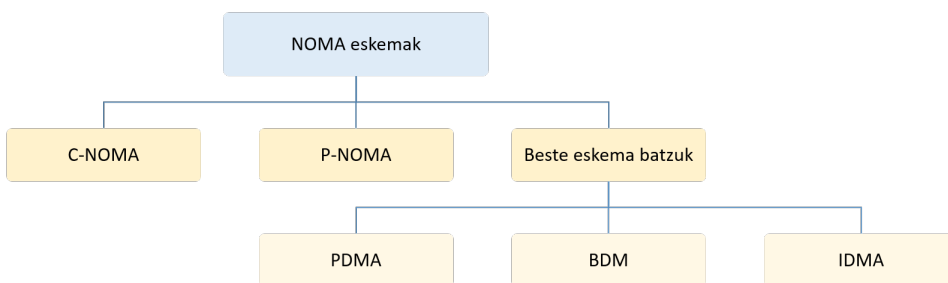


IRUDIA 1.4: OMA eta NOMA tekniken zerbitzuen ahalmenen alderaketa harrera-baldintza desberdinetarako

Gainera, 0 dB eta 20 dBko SNRak dituzten zerbitzuetan, 0,4 bps/Hz eta bi bps/Hz-ko irabazia lor daiteke S_1 eta S_2 rako, hurrenez hurren. Horrez gain, NOMAak OMArekiko duen irabazia zuzenean lotuta dago eskaintzen diren zerbitzuen asimetriarekin. Izan ere, zenbat eta handiagoa izan transmititutako zerbitzuen arteko asimetria, orduan eta handiagoa da NOMA lortutako irabazia, OMA sistemekin alderatuta.

Laburbilduz, NOMA teknikek hainbat abantaila dituzte OMArekin alderatuta. Hona hemen onuren deskribapen labur bat:

- *Kanalaren ahalmenaren ustiapena:* goian erakusten den bezala, NOMA teknikek espektrero-eraginkortasunaren errendimendua nabarmen hobetzen dute OMA teknikekin alderatuta. Izan ere, NOMAren gaitasunaren muga OMArena baino handiagoa da kasu guztietan. Horregatik, NOMA espektrero baliabideen ustiapen hobea eskaintzen du.
- *Konektibitate masiboa:* NOMA baliabideen kudeaketa tekniketari sartzeak esan nahi du zerbitzuetako erabilgaitasun kopurua edo eskaintutako zerbitzu kopurua ez dagoela kanalean dauden baliabide ortogonalen kopuruaren arabera mugatuta. Beraz, NOMA OMA baino erabilgaitasun gehiagori aldi berean sarbidea eskaini diezaieke.



IRUDIA 1.5: NOMA teknika adierazgarrienen sailkapena

Hortaz, NOMA hobeto egokitzen da 5G zerbitzuetarako espero diren konexio masiboetara.

- *Ingurunerako sarrera latentzia baxua:* OMA sarbide-teknikak dituzten komunikazio-sistema tradizioaletan, 4G kasu, erabiltzaile bakoitzak estazio basera konektatzeko eskaera bat bidali behar du. Gero, estazio baseak erabiltzaile bakoitzaren konexioa administratzen du erabilgarri dauden baliabideen arabera, eta erabiltzaileari konexioa hasteko prest dagoen mezu bat bidaltzen dio. Zalantzarik gabe, ingurunera sartzeko mekanismo horiek transmisioari lotutako latentzia nabarmen handitzea eta gainkarga areagotzea dakarte. Zehazki, [53]-ren arabera, Long Term Evolutionen (LTE) oinarritutako sarbide-mekanismoek 15,5 ms inguruko latentzia pairatzen dute, 1.1 taulan deskribatutako mugen oso gainetik dagoena. Aitzitik, NOMAn oinarritutako ingurunerako sarbide teknika batzuek (adibidez, kontrolik gabeko sarbide anizkoitzak) ez dute konexio-eskaerarik behar. Izan ere, harreran detekzio-teknika egokiak erabiliz, erabiltzaile bakoitzaren informazioa bereiz daiteke, horrela, ingurunerako sarbidearekin lotutako latentzia eta gainkarga murriztuz [54].

1.2.1.2 NOMA tekniken taxonomia

NOMA teknika espezifikoetan bana daitekeen kontzeptu zabala da. Hain zuzen ere, literaturan aurki daitekeen banaketa esanguratsuenetako bat NOMA teknikak bi familia handitan banatzean datza: potentzia domeinuko NOMA (P-NOMA) eta kode domeinuko NOMA (C-NOMA) [21, 55, 56, 57]. 1.5 irudian erakusten den bezala, sailkapen generiko honetatik kanpoko beste NOMA teknika batzuk daude. Atal honen helburua existitzen diren NOMA teknika garrantzitsuenak deskribatzea da.

Alde batetik, C-NOMA teknikak zerbitzuaren/erabiltzailearen multiplexazioa kodeen domeinuan oinarritzen dute. Bereziki, C-NOMA kontzeptua 3Gn erabilitako CDMA eskema klasikoetan inspiratua dago, non erabiltzaile askok eskura dauden baliabide guztiak partekatzen dituzten (hau da, denbora eta frekuentzia domeinuak). Hala ere, CDMA eta C-NOMA eskemen arteko desberdintasun nagusia C-NOMAn hedapen-sekuentziak sekuentzia sakabanatueta edo korrelazio gurutatu baxuko sekuentzia ez-ortogonaletara mugatzen direla da [21].

Oro har, C-NOMA teknikak hainbat azpifamiliatan sailka daitezke. Literaturan topa daitekeen C-NOMAn lehen tekniketako bat dentsitate baxuko hedapenean oinarritutako CDMA (Low-Density Spreading, LDS-CDMA) da [58]. Teknika hau, hedatutako kodifikazio sekuentzietan oinarritutako NOMAn lehen aurkezpena da eta bere helburu nagusia, oinarritzko CDMA sistemen sinbolo bakoitzean interferentzia efektua murriztea da [59]. Ondoren, OFDM sistemekin konbinatzean dentsitate baxuko hedapenean oinarritutako OFDM (LDS-OFDM) aurkeztu zen, LDS-CDMAren eboluzio bezala [60]. Kasu honetan, informazio-sinboloak, lehenik, dentsitate baxuko banaketa-sekuentzien bidez banatzen dira, eta ondoriozko txipak, azpi-eramaileen multzo batean transmititzen dira [61, 62]. Azkenik, C-NOMA tekniketari egin berri den aurrerapen nagusietako bat kode sakabanatuaren sarbide anizkoitza da (Sparse Code Multiple Acces, SCMA) [63]. SCMA LDS-CDMA oinarritzen den arren, informazio-bitak zuzenean kode-hitz sakabanatu desberdinei esleitu dakizkieke, bit-esleipena zein bit-dispersioa konbinatzen baitira [64]. LDS-CDMA sistemarekiko SCMAren abantaila nagusia hartzailearen aldean konplexutasun txikiagoa dakarrela eta errendimendua hobetzen duela da [65, 66].

Bestalde, Cover eta Bergmans-ek lehen P-NOMA ikuspegia garatu zuten [67, 68] lanetan, gainjartze-kodifikazioaren (Superposition Coding, SC) kontzeptuarekin. SCn hainbat hartzailearen informazioa baliabide berean eta aldi berean transmititzen da. Gero, hartzailean, hurrenez hurreneko interferentzien ezeztatze modulu bat behar da (Successive Interference Cancellation, SIC), hartzaile bakoitzean gainjarritako informazioa deskodetzeko. SIC moduluaren oinarritzko printzipioa erabiltzaile-seinaleak hurrenez hurren deskodetzen direla da. Lehenengo seinalea deskodetutakoan, jasotako seinaletik kentzen da, zeinetan seinale guztiak konbinatuta dauden. Ondoren, hurrengo seinalea deskodetu eta kendu egiten da. Prozesu iteratiboa errepikatu egiten da seinale guztiak behar bezala deskodetzen diren arte. Garrantzitsua da nabarmentzea SIC prozesuan seinale espezifikoko bat deskodetzerakoan, gainerako seinaleak interferentzia gisa tratatzen direla. Oro har, P-NOMAk hainbat seinale izan ditzake hainbat geruzatan antolatuta, non geruza bakoitzak transmisoreak

transmititutako potentzia osoaren zati bat hartzen duen. P-NOMAREN ezaugarrietako bat geruza bakoitza modu independentean konfiguratu daitekeela da, helburu desberdinei aurre egiteko. Beraz, konfigurazioa modulazioaren, kodifikazioaren eta injekzio-mailaren arabera da, geruzen arteko potentzia-banaketa gisa definitzen dena, eta g (edo Δ , dB-tan neurtzen bada) bidez deskribatzen dena. P-NOMA seinale generikoen multzoa honela adieraz daiteke:

$$x_{P-NOMA}(k) = x_{S1}(k) + g_1 \cdot x_{S2}(k) + \dots + g_{N-1} \cdot x_{SN}(k) \quad (1.1)$$

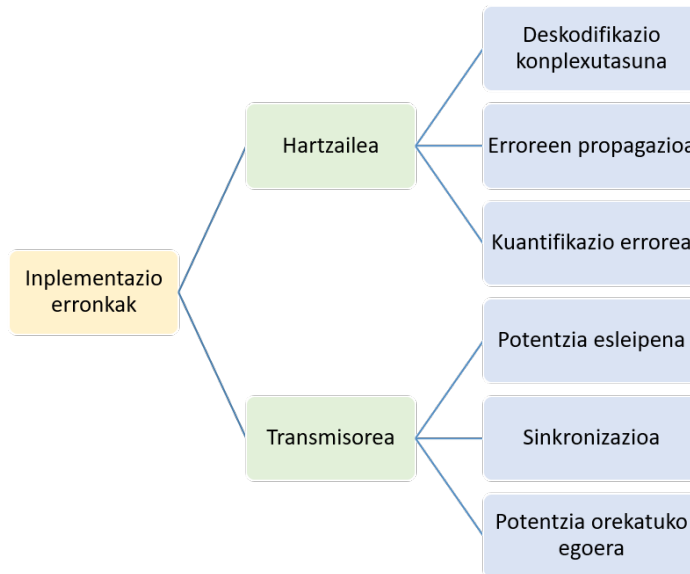
non $x_{P-NOMA}(k)$ P-NOMA seinalea eta $x_{S1}(k)$, $x_{S2}(k)$ eta $x_{SN}(k)$, $S1$, $S2$ eta SN erabiltzaileentzat transmititutako seinale independenteak diren. Gainera, k azpikanalaren indizea da. P-NOMA seinalea sortzeko injekzio-mailak aplikatuz, transmititu beharreko zerbitzuen artean banatzen da transmititzeko potentzia osoa, honela:

$$\sigma_i = \frac{10^{\frac{\Delta_i-1}{10}}}{\sum_{i=1}^N 10^{\frac{\Delta_i-1}{10}}} \quad (1.2)$$

non σ_i i geruzari esleitutako potentzia den, zeina normalizatuta dagoen (hau da, $\sum \sigma_i = 1$), eta goiko geruzari dagokion injekzio-maila $\Delta_0 = 0$ dB da.

C-NOMA eta P-NOMA NOMA eskemen familia adierazgarrienak diren arren, badira gaur egun ikertzen ari diren beste NOMA eskema batzuk [69]. Adibidez, patroia banaketa bidezko sarbide anizkoitza (Pattern Division Multiple Access, PDMA) hainbat eremutan ezar daitekeen etorkizun handiko eskema da [70]. Lehenik, transmisorearen moduluan, PDMA patroia ez-ortogonaletan oinarritzen da, eta patroia horiek aniztasuna maximizatuz eta erabiltzaile askoren arteko gainjartzeak minimizatuz diseinatu dira. Orduan, multiplexazio etapa kode-domeinuan, domeinu espazialean, potentzia-domeinuan edo era konbinatuan aplikatu daiteke. Beste aukera bat bitak zatitzearen bidezko multiplexazioa (Bit-Division Multiplexing, BDM) da [71]. BDM beharrezko loturako transmisioetara bideratuta dago. Orokorrean, modulazio hierarkikoan oinarritzen da eta erabiltzaile multiplexatuen baliabideak bit-mailan banatuta daude. BDM eskemetako baliabideen esleipena biten domeinuan ortogonalak bada ere, erabiltzaileen seinaleek konstelazio bera partekatzen dute, eta horrek sinboloen modulazioaren domeinuan gainjartzeak sortzen ditu. Azkenik, trukaketa bidezko banaketa duen sarbide anizkoitza (Interleave Division Multiple Access, IDMA) aurkeztu behar da [72]. Kasu honetan, IDMAk bitak elkarlotzen ditu sinboloak eta sakabanatutako sekuentziak biderkatu ondoren. [72]-ren arabera, IDMAk CDMA gainditzen du.

Atal honetan, zenbait NOMA eskema aurkeztu diren arren, doktorego



IRUDIA 1.6: NOMA tekniken implementazio-erronka adierazgarrienen sailkapena

tesi hau konplexutasun txikiko P-NOMA sistemetan zentratzen da, konplexutasunaren eta errendimenduaren arteko konpromiso hobe ematen baitute [73]. Beraz, honetatik aurrera, NOMA eta P-NOMA berdin erabiliko dira, eta NOMA erabiltzen den guztietan P-NOMA izango da.

1.2.1.3 Implementazio erronkak

Haririk gabeko komunikazio-sistemetan NOMA erabiltzeak hainbat abantaila dituen arren, implementatzean zenbait zailtasun ager daitezke. Hori dela eta, azpiatal honen helburua NOMA implementatzearekin lotutako erronkak aurkeztea eta aztertzea da. 1.6 irudiak atal honetan aurkeztuko diren implementazio-erronka nagusien laburpena erakusten du, transmisoreetan eta hartzaileetan sailkatuta.

Deskodifikazio konplexutasuna. Lehen erroreak, eta ezagunena oro har, deskodetzearen konplexutasuna areagotzea da. Multiplexazio ortogonaleko eskemekin alderatuta, NOMA eskemetan erabilitako deskodetze-etapak konplexutasun gehigarri bat eskatzen du, geruzak berreskuratzeko etaparen ondorioz. Teknika hedatuenetako bat SIC modulua da, zeinak, hartzaile jakin bati zuzendutako informazioa lortzeko, lehenik eta behin nahi den geruzaren gainetik kokatutako datu-geruzak deskodetu egin behar baititu [74]. Beste aukera bat [75] lanean aurkezten da, azpiko seinaleen konstelazioaren ezagutzan

oinarritzen dena. Hala ere, deskodetzailearen konplexutasunak handia izaten jarraitzen du, eta, ondorioz, konplexutasun orokorrak gora egiten du sareko erabiltzaileen kopuruak gora egin ahala. Horregatik, batez ere latenziarekiko intoleranteak diren komunikazioetan, NOMAren deskodetze prozesuarekin lotutako konplexutasuna murrizten duten irtenbideak behar dira. Komunikazio zelularretan erabil daitezkeen irtenbide bat erabiltzaileak kanalaren egoeraren arabera taldekatzea da, eta multicast transmisioak erabiltzea, SIC moduluko deskodetze-prozesua talde bakoitzeko informazioan oinarritu dadin. Erabiltzaileak taldekatzeko algoritmoak erabil daitezke, hala nola [76] erabiltzaile-taldeak sortzeko. Gero, [20]-n, deskodetze sekuentziala onuragarria dela soilik informazioa ondo deskodetzeko probabilitate handia dagoenean nabarmentzen da. Lelo hori kontuan hartuta, egileek deskodetze-eskema bat garatu zuten, kalkulaturako ondo deskodetzeko probabilitatean oinarrituta.

Erroreen propagazioa. SIC moduluarekin erlazionaturako beste erronka garrantzitsu bat erroreen propagazioarekin lotuta dago. Berezi, SIC sisteman errore bat gertatzen denean, errore hori hurrengo geruzetara hedatzen da, beheko geruzen deskodetzeari eraginez eta behar bezala ez lortzea eraginez. Errorearen hedapena konpentsatzeko, geruzarik altuenak kode sendoagoekin kodetu behar dira. Izan ere, [77]-ko egileek errorea hedatzeak deskodifikazioan duen eragina ia arbuigarria dela kanal-baldintza onak dituzten erabiltzaileak kanal-baldintza txarrak dituzten erabiltzaileen gainetik antolatzen direnean frogatu zuten. Beraz, sendotasunaren eta errendimenduaren arteko konpromisoa onartu behar da.

Kuantifikazio errorea. Kuantifikazio-errorea NOMA sistemen SIC moduluarekin lotutako beste arazo bat da. Jasotako seinaleen potentzia oso desorekatuta dagoenean, analogikotik digitalerako bihurtailuak (ADB) tarte dinamikoa zabala behar du bereizmen handia lortzeko. Hala ere, ezarritako kuantifikazio-mailen kopurua mugatua denez, egoera zailtako kanaletan jasotako seinaleen kuantifikazio-zarata altua izan liteke (normalean beheko geruzetan kokaturakoak). Beraz, SIC moduluen errendimenduaren eta kuantifikazio-prozesuaren kostuaren arteko konpromisoa onartu behar da.

Potentzia esleipena. NOMA oinarritutako sistemetan, geruza bakoitzaren energia esleipenak zerbitzu bakoitzaren errendimendua zehazten du, eta, ondorioz, sarearen ahalmena. Izan ere, injekzio-maila (Injection Level, IL) oso altua erabiliz gero, goiko geruzaren (Upper Layer, UL) sendotasuna oso handia da, baina beheko geruzak (Lower Layer, LL) deskodetzeko beharrezkoa den SNRa nabarmen handitzen da. Aldiz, IL baxuek LLa errazago deskodetzea eragiten dute, baina ULa konprometitzen dute. Horregatik, energia-esleipen optimoarekin lotutako

konplexutasuna kritikoa da NOMA sistemetan. Normalean, indar handiko algoritmoak IL konbinaziorik onena eta geruza bakoitzaren konfigurazioa eta geruzaren erabiltzaileak zehazteko erabiltzen dira. Hala ere, horrelako algoritmoek kostu konputazional izugarria dute. Beraz, [78] bezalako algoritmoak behar dira NOMA parametroen konfigurazio onena modu adimentsuan balioesteko.

Sinkronizazioa. NOMA sistemen geruzen arteko sinkronizazioa literaturan asko ikertu den beste erronka bat da. Beheranzko loturako komunikazioetan, estazio baseak erabiltzaile bakoitzaren transmisio guztiak kudeatzen ditu, eta horrek sinkronizazio perfektua aplikatzea ahalbidetzen du. Hala ere, sinkronizazio perfektu hori ezin da goranzko loturako komunikazioetan bermatu; izan ere, erabiltzaileak sare osoan banatuta daude, eta, oro har, posizioa etengabe aldatzen dute. Efektu horrek gainjarritako kodeen jasotako sinboloak lerrokaturik ez egotea eragiten du, eta, beraz, deskodetzearen errendimendua murrizten da. Hortaz, NOMA sistemen errendimendua, zati batean, goranzko loturako komunikazioetan parte hartzen duten erabiltzaileen denbora-diferentziaren arabera da [79]. Irtenbide posibleetako bat seinaleak detektatzeko gaitasuna handitzea da, geruza bakoitzaren sinboloak berrantolatzeke gainerako komunikazioen sinboloez baliatuz [80].

Potentzia orekatuko egoera. Azkenik, agertoki mota espezifiko bati lotutako erronka bat dago: potentzia orekatuko egoera. 1.4 irudian ikusten denez, zerbitzuen arteko desoreka zenbat eta handiagoa izan, orduan eta handiagoa da NOMAren irabazia. Hala ere, zerbitzuak simetrikoak direnean, NOMAren errendimendua murriztu egiten da eta, kasu batzuetan, OMA sistemena baino okerragoa ere izan daiteke. Beraz, funtsezkoa da zerbitzuaren konfigurazioa planifikatzea NOMAren errendimendua behar bezala maximizatzeke.

1.2.1.4 NOMAren aplikazioak

NOMA broadcast sistemetan

Ikerkuntza komunitatean, NOMA aplikazio askotarako erabiltzea proposatu da. Hala ere, mugari garrantzitsuenetako bat irrati-difusio bidezko komunikazioen arloan lortu da. Izan ere, NOMA tekniken arrakastaren adibide garrantzitsu bat 2017an gertatu zen, lurreko telebista digitalaren (LTD) alorrean, alegia. Estatu Batuetako LTD estandarrik, ATSC 3.0 [81] izenekoak, NOMA oinarritutako konplexutasun baxuko soluzio bat estandarrean sartu zuenean. Soluzio hau informazioa geruzatan banatzearen bidezko multiplexazioa (Layered Division Multi-

plexing, LDM) bezala ezagutzen da [82]. Arrakasta horren funtsezko adierazleak errendimenduaren, fidagarritasunaren eta ahalmenaren aldi bereko hobekuntza izan zen.

LDMren ideia Cloud Transmission (Cloud Txn) sistematik sortu zen [83]. Cloud Txn geruza ugariko sistema malgu bat da, espektra gainjartzeko teknologia erabiltzen duena ezaugarri eta sendotasun ezberdineko programa fluxu ugari aldi berean irrati frekuentzia (Radio Frequency, RF) kanal batean emateko. Hortik aurrera, Cloud Txn kontzeptuak gaur egun LDM bezala ezagutzen denerantz eboluzionatu zuen. Bereziki, LDM, Cloud Txn bezala, bi geruzako transmisio-egitura bat da, aldi berean potentzia eta sendotasun maila desberdineko hainbat datu-fluxu ematen dituen xede-erabiltzaile ezberdinentzat (adibidez, hartzaile mugikor eta finkoak). Zehazki, LDM zerbitzu mugikorak transmititzeko potentzia-esleipen handiko ULa konfiguratzeko diseinatu zen, bai eta hartzaile finkoentzako SNR eskakizun handiekin lotutako gaitasun handiko zerbitzuak emateko ere LL geruzan [82].

LDM ATSC 3.0 estandarrean sartzeko funtsezko arazoietako bat transmisio-ahalmena handitu zuela konplexutasun-maila txikiak asumituz izan zen. Zehazki, konplexutasun txikia parametro batzuen diseinu egokiaren bidez lortu zen. Lehenik eta behin, transmisio-potentziaren, seinale-kodifikazioaren eta modulazioaren konfigurazio posibleak ATSC 3.0 estandarrean definitutako balio-multzo batera mugatu ziren [81]. Ondoren, LDM transmisorea seinalearen egitura eta segidako geruzen oinarritzko seinaleak behar bezala lerrokatze diseinatu zen, hartzailearen aldean segidako seinalea ezeztatze deskodetze-algoritmoa ahalbidetzeko, konplexutasuna nabarmen handitu gabe. Horrez gain, oso SNR baxuko seinaleak deskodetzea ahalbidetu zen, dentsitate baxuko parekotasuna egiaztatze kodeak (Low-Density Parity-Check, LDPC) barne-kode gisa erabiltzea erabaki zelako. Azken belaunaldiko LDPC kodeek Shannon-en mugatik oso gertu dauden errendimendu-balioak dituzte, dB erdiaren inguru [84]. Gero, kanpo-kodeetarako hiru aukera hartu ziren kontuan: Bose-Chaudhuri-Hocquenghem (BCH) [85] kodeak, 32 biteko erredundantzia ziklikoaren egiaztapena (Cyclic Redundancy Check, CRC), eta kanpo-kodifikaziorik ez erabiltzea. Bestela esanda, LDMk gainjarritako kodifikazioari esker errendimendu-irabaziak lortzen ditu konplexutasun onargarriekin.

Konplexutasun txikia LDMren alderdi nagusietako bat denez, lan batzuetan sakonki aztertu da [86, 87]. Egileek frogatu zuten, 16 puntuko konstelazio ez-uniformeko (Non-Uniform Constellation, NUC) eta 256-NUCeko konfigurazioa erabiliz ULan eta LLan, hurrenez hurren, LDM konfigurazioa, LLaren edukia soilik transmititzen den kasuarekin alderatuta konplexutasuna %20 baino ez dela handitzen. Kalkulu hori

LDPC kodeek behar duten iterazio-kopuruan oinarritzen da. Izan ere, LDMren UL zerbitzu tipiko baterako SNR tartea kontuan hartuta (hau da, 0-5 dB), LDPC deskodetzaileak 50 iterazio baino gutxiago behar dituela frogatuta dago. Beraz, LLaren deskodetze-prozesuarekin erlazionatutako konplexutasun igoera %20 arte da (hau da, 10/50). Horrek esan nahi du geruza bakarreko (hau da, LL soilik) LDPC deskodetzaileak 50 iterazio egin behar dituela; aldiz, LDPC deskodegailuak, bi geruzako LDM hargailu batean, 60 iterazio egin behar ditu guztira. Nabarmendu behar da, halaber, ULa deskodetzeko prozesuak ez dakarrela konplexutasuna areagotzea.

Konplexutasun-kostu txikiarekin batera, ATSC 3.0 sisteman parte hartzeko LDM hautatzeko beste funtsezko arrazoia ahalmen-irabazia izan zen. Zehazki, LDMren ahalmen-irabazia OMA teknikekin alderatuta, askotan frogatu da edozein teknologia ebaluatzeko erabiltzen diren garapen-mailetatik abiatuta: teorikoki [82, 88], simulazioen bidez [89, 90], eta neurketen bidez [91, 92]. Horregatik, LDM irrati-difusioaren arlotik kanpoko beste komunikazio-estandar batzuetarako erabiltzea proposatu da. Adibidez, LDM eta 4G konbinatzea proposatu zen [93]-n eta [94]-n, non LDMk multicast baliabideak esleitzeko dituen onurak eta zerbitzuen konbergentzia nabarmendu ziren, hurrenez hurren. Gero, lan berriagoetan, LDM eta 5Gren erabilera konbinatua proposatu da [95, 96, 97], non eskaintzen den ahalmenaren hobekuntza eta 5G ekosistemaren erabilera potentzialei erantzuna emateko malgutasuna diren proposamenen sendotasun nagusiak.

Azkenik, aipatzekoa da Europako LTD sistemaren (hau da, Digital Video Broadcasting, DVB) beste ekimen bat ere izan zela bere estandarrean LDMn oinarritutako geruza anitzeko seinale-egitura bat sartzeko. Teknologia horri Wideband reuse-1 (WiB) [98] izena eman zitzaion, eta transmisorearen UHF bandako kanal guztiak erabiltzean eta transmititutako potentzia kanal horien bidez berdin banatzean zetzan. Transmisio-plangintza hau eta kodifikazio-konfigurazio sendoak erabiliz, hala nola 1/2 koadratura-faseko desplazamenduagatik kodifikazioa (Quadrature Phase Shift Keying, QPSK), WiB seinalea UHF kanal bakoitzean transmititutako seinale nagusiaren azpitik zenbait dBtara transmitituko litzateke. Gaitasun irabazi nabaria aurreikusi zen, konplexutasun/kostu igoera onargarrien kontura, azkenean WiB ez zen aintzat hartu DVB estandarreko.

NOMA sare zelularretan

Azken urteetan, NOMA teknikak 3. belaunaldiko elkartze-proiekturako (3rd Generation Partnership Project, 3GPP) ere erakargarriak

TAULA 1.5: 3GPPk NOMA eskemei buruz egindako azterlanen laburpena

Release	Urtea	TR	Teknologia	Deskribapena	Erabakia
Rel-12	2014	36.866	NAICS	Zelulen arteko interferentziak ezeztatzeko eskema bat garatzea	Onartu
Rel-13/14	2016	36.859	MUST	Beharazko loturako erabiltzaile anitzeko eske-men analisia ematea	Onartu
Rel-16	2018	38.812	Goranzko NOMA	Goranzko loturako NOMAren hautagai potentzialen azterketa bat egitea 5G NRako	Baztertu

izan dira, errendimenduan dituen onurak direla eta. Beraz, atal honen helburua NOMA teknikak 3GPP lan-elementuen (Work-Item, WI) barruan izan duten bilakaeraren ikuspegi orokorra ematea da. 1.5 taulak orain arte NOMAri buruz argitaratu diren 3GPPren Txosten Teknikoen (Technical Report, TR) laburpena erakusten du.

3GPPk NOMArekin izan zuen lehen kontaktua 12. bertsioan (Release 12, Rel-12) gertatu zen, ikerketa-proiektu berri bat proposatu zutenean: sarek lagundutako interferentzia ezeztatzea eta ezabatzea (Network Assisted Interference Cancellation and Suppression, NAICS) [99]. NAICS, LTErentzat ez ezik, interferentziak ezeztatzeko beste eskema batzuetan ere erabil zitekeen sistema unibertsala zen. NAICSen ideia nagusia seinaleztapenaren eta estimazio itsuaren informazioa erabiltzea interferentzia zelularren gainean beharrezkoak diren parametroak lortzeko eta, ondoren, hargailu aurreratuetan interferentzia ezeztatzeko da [100].

Ondoren, 3GPPk Rel-13rako azterketa-puntu berri bat onartu zuen beharazko loturaren erabiltzaile anitzeko gainezarpenaren transmisioari (multiuser superposition transmission, MUST) [101] dagokionez. Taldearen helburu nagusia beharazko loturako erabiltzaile anitzeko transmisioeko eskema eraginkorretarako hautagai potentzialen azterketa bat ematea zen. Lanean zehar ebaluatu ziren KPI nagusiak sistema-mailako irabazia eta konplexutasunaren eta errendimenduaren arteko konpromisoa izan ziren. Zehazki, proposatutako MUST soluzioa SCetan oinarritu zen, eta hainbat sarbide-kanalen ahalmena lor zezakeen, SIC moduluari esker [102]. Txosten teknikoa arrakastatsua izan zen eta Rel-14an onartu zen.

Azkenik, 5G NRri dagokionez, bi ikerketa-lerro hartu dira kontuan: beharazko loturako eta goranzko loturako NOMA. Beharazko loturako NOMAri dagokionez, 5G NRn MUSTen aplikazio zuzena erraza zirudien. Alabaina, 3GPPk beharazko loturako NOMAn zuen interesak behera egin zuen MIMO masiboan oinarritutako teknologiek jada irabazi esanguratsuak eskaintzen zituztelako, eta NOMAren integrazioak ez zuen gaitasun/konplexutasun konpentsazioa gainditzeko adinako onurarik emango [103]. Horregatik, beharazko loturako NOMA ez da 5G

NRrako kontuan hartzen. Aldiz, goranzko loturako NOMA eskemak erakargarriagoak ziren 3GPPrentzat, eta goranzko loturaren kontzesiorik gabeko NOMA transmisioari buruzko azterlan bat onartu zen [104]. Proiektuaren helburua OMA eskemetan goranzko lotura duten NOMA teknikak dituzten onurak aztertzea eta 5G NRrako kontuan hartuko zen erabakitzea zen. Azkenik, NOMAk kasu batzuetan erakutsi zuen errendimenduaren degradazioa izan zen 17. bertsioan lan elementutzat ez hartzeko arrazoi nagusia [20, 105].

NOMA beste aplikazio berri batzuetarako

NOMA eskemek broadcast inguruneetan eta banda zabaleko komunikazioetan (hau da, 3GPP) izan duten bilakaera aztertu ondoren, atal honetan, NOMAren eta beste ikerketa-arlo espezifikokoago batzuen arteko konbinazioa aztertzen duten argitalpen berrienetako batzuk aztertzen dira. 1.6 taulak atal honetan aztertutako lan teknikoan laburpena erakusten du.

MIMO masiboa. Lehenengo teknologia MIMO masiboa da, sarearen espektroraginkortasuna eta erabiltzailearen konektibitatea izugarri handitzen duena. MIMO masiboa asko aztertu da OMArekin konbinatuta, baina NOMArekin batera erabiltzeak errendimendu tasa hobeak ekar ditzake. Lehen azterketetako bat [106]-n agertzen da, non NOMAn oinarritutako MIMO masiboak OMA gainditzen duela frogatzen den. Gainera, batuketa-tasaren balioak lor daitezke zehaztasun handiko kanal-egoerari buruzko informazioa lortzen denean eta taldeen arteko interferentziarik ematen ez denean. Gero, [107] lanaren egileek MIMO-NOMAk zelula anitzeko inguruneetan duen errendimendua aztertzen dute, eta erabiltzaileak sailkatzeko eta kanalaren kobariantza-informazioan oinarritutako pilotuen esleipena egiteko eskema bat proposatzen dute. Bestalde, [108] lanean, baliabideen esleipenak MIMO-NOMAn duen eragina aztertu nahi da. Bereziki, hiru dimentsioko baliabideak esleitzeko eskema bat definitzen dute (hau da, maiztasuna, espazioa eta potentzia-eremua), etorkizun handiko errendimendu-hobekuntzak erakusten dituen. Horren ostean, sarearen eta sistemaren parametroek MIMO-NOMA komunikazio-sistemetan duten eragina kuantifikatzea da [109]-ren helburu nagusia. Kasu honetan, MIMO-NOMA birtransmisio komunikazioetarako probatzen da. Aztertutako parametroak estazio baseko antena kopurua, nodo kopurua eta transmititutako potentzia dira. Azkenik, [110]-n, lor daitezkeen tasa-balioak egoera ez-idealean zenbatesten dira. Bereziki, egileek beamforming-aren orientazioa ezezaguna dela asumitzen dute eta SIC moduluak modu inperfektuan funtzionatzen duela.

MIMO masiboa mmWave bandetan. Erabilera-kasu berriek datu-

TAULA 1.6: Aplikazio ezberdinetarako NOMAri buruzko ekarpen nagusien laburpena

Ikerketa ar- loa	Onura	[Eref] - Deskribapena
MIMO- NOMA	Konektibitate masiboa, Ahalemen handia, Efizientzia espektrala	[106] - Prezisio handiko CSI eta talde-interferentziarik gabe bidez lor daitekeen batura tasaren definizioa
		[107] - Erabiltzaileen sailkapena eta kanaleko kobariantzan oinarritutako pilotuen esleipena definitzea
		[108] - 3D baliabideen esleipena diseinatzea MIMO masiborako, NOMA bidez lagunduta
		[109] - Espektrero-eraginkortasuna zehaztea MIMO-NOMA parametro espezi-fikoen arabera
		[110] - Beamforming-aren ziurgabetasuna dagoenean eta kanala estimatzeko eta SIC hondar-interferentzia dagoenean lor daitekeen datuen abiadura
mmWave NOMA	Alhamen handia	[111] - mmWave MIMO-NOMAn abiadura-muga lorgarrien definizioa
		[112] - SISO kanal ugaritan oinarritutako berrelikadura txikiko NOMA diseinu bat proposatzea
		[113] - Ebazpen finitudun aurrekodedzaile analogikoa, hardwarearen kostua murrizteko
		[114] - Beamforming-aren ebazpen finitu analogikoa konpentsatzeko NOMA erabili
		[115] - Beamforming-aren deslerrokatzearen inpaktua zehaztea mmWave MIMO-NOMAn
NOMA kooperatiboa	Fidagarritasuna, Segurta- suna, Efizientzia espektrala	[116] - Full-duplex transmisioetan oinarritutako NOMA kooperatiboa
		[117] - Half-duplex/full-duplex konmutazio algoritmo baten definizioa
		[118] - Erabiltzailearen distantzian oinarrituta birtransmisio eskema bat definitzea
		[119] - CoMP transmisioen definizioa
		[120] - CoMPn oinarrituta zelula-ertzeko erabiltzaileentzako beamforming eskema koordinatua
		[121] - Sareen arteko interferentzia murrizteko beamforming eskemak sare anitzeko MIMO-NOMAn
NOMA ko- munikazio kognitiboetan	Efizientzia espektrala, Ahalmen handia	[122] - CR sare handietan NOMA erabiltzeko eredu estokastikoa definitzea
		[123] - CR-NOMAn konbinazioa birtransmisio komunikazioetarako
		[124] - Espektroroaren eraginkortasunerako eta erabiltzailearen ekitaterako NOMA-CR eredu definitzea
		[125] - Erabiltzaileak parekatzeak errendimenduan duen eraginaren zenbate-spena
		[126] - Antena anitzen transmisio ingurunetarako AN transmisioa barneratzen duen komunikazio-sistema definitzea
PHY segurtasuna NOMA erabiliz	Segurtasuna, Zuhurta- suna, Anti- jamming	[127] - Sekretuaren definizio analitikoa SISO-NOMA erabiliz ikusmiratzaile baten aurrean
		[128] - Interferentzia eta zilegizko transmisio konbinatua bi norabideko sare batean, ikusmiratzaileen presentziapen
		[129] - Interferentzia- eta informazio-seinale txandakatueta oinarritutako elkarlaneko transmisio eskema
		[130] - TAS MIMO-NOMA sistemetarako segurtasuna handitzeko mekanis-motzat proposatzea
		[131] - NOMA-VLC eta OFDMA alderatzea beheranzko lotura duten bi erabiltzaileentzat
NOMA- VLC	Ahalmen handia	[132] - NOMAn potentzia esleipena erabiltzailearen kanalaren kalitatearen arabera ezartzeko algoritmo baten definizioa
		[133] - QoS bermatzen duen probabilitatearen adierazpenaren definizioa beheranzko loturako NOMAn
		[134] - Chebyshev aurrekodedzaile baten proposamena kanal ez-linealen errendimendua hobetzeko
		[135] - NOMA-VLCn lor daitekeen batura-tasaren adierazpena kalkulatzeko, erabiltzailearen mugikortasuna kontuan hartuta
		[136] - NOMA-OFDMA-VLC noranzko biko sistemaren proba esperimental

abiadura oso altuak eskatzen dituztela kontuan hartuta, mmWave banden erabilera premia bihurtu da. Horregatik, hainbat ikerketa-lan bideratu dira mmWave bandetan MIMO-NOMArekin jarduna aztertzerako. Aipatu behar da MIMO teknika espezifikoak garatu behar direla uhin milimetrikoei bandetarako, frekuentzia-banda horien erronka bereziak direla eta. Lehenik eta behin, lor daitezkeen datuen abiadura-mugak [111]-n deskribatzen dira, mmWave bandetan MIMO masiboa inplementatzeko. Ondoren, [112]-ren egileek sarearen konplexutasuna eta kongestioa murrizteko interesa dute eta, horretarako, berrelikadura baxuko NOMA komunikazio arkitektura bat proposatzen dute. Kasu horretan, errendimendu-irabazien eta konplexutasunaren arteko konpromisoa onartu behar da. MIMO komunikazioek suposatzen dituzten hardware-kostuei dagokionez, oro har, onartuta dago aurrekodedutailer analogikoak erabiltzean bereizmen finitua asumitu behar dela [113]. Arazo hori kontuan hartuta, [114]-ren egileek MIMO-NOMA erabiltzea proposatzen dute mmWave bandetan, beamforming analogikoak eratzeko bereizmen finitua konpentsatzeko. Azkenik, [115] argitalpenean, beamforming-aren deslerrotatzeak mmWave ingurunean duen inpaktua aztertzen da, ikusmen eta ikusmen-zuzenik gabeko (Line-of-Sight/Non-Line-of-Sight, LOS/NLOS) baldintzetarako.

Komunikazio kooperatiboak. Sarearen ahalmena eta komunikazioaren fidagarritasuna hobetzeko beste aukera bat komunikazio kooperatiboak erabiltzea da. Teknologia horren ideia nagusia sareko nodoen arteko lankidetzaren ahalbidetzea eta eskura dauden baliabideak partekatzea da, hala nola transmisio-eskemak edo energia trukaketa. Adibidez, [116] lana komunikazioen errendimendua hobetzeko bideratuta dago, NOMA kooperatiboa erabiliz full-duplex komunikazioetan. Ildo honetan, [117] lanaren egileek algoritmo hibrido bat proposatzen dute, modu adimentsuan half-duplex eta full-duplex artean aldatzen dena sarean zehar ausaz banatutako birtransmisioaren komunikazioetan. Gero, [118]-ko egileek NOMA eskema bat aurkezten dute, bi etapako birtransmisioez lagundua, urruneko erabiltzaileen komunikazioaren fidagarritasuna hobetzeko. Bereziki, xede-erabiltzailea hurbil dagoela uste bada, estazio baseak zuzenean ezartzen ditu komunikazioak. Urrutiko posizioetan dauden erabiltzaileentzat, ordea, birtransmisio-nodo batek hartzen du transmisore papera. Urruneko erabiltzaileen zerbitzu-kalitateari dagokionez, puntu anitzeko transmisio kooperatibo koordinatuak (Coordinated Multi-Point, CoMP) diseinatu ziren [119]. Hain zuzen ere, CoMP erabiliz, hainbat estazio base koordinatzen dira, erabiltzaileari zuzendutako beamforming-ak aldi berean kudeatzeko sarearen ertzeko erabiltzaileen errendimendua hobetzeko [120]. CoMPren antzera, [121]-n, zelula anitzeko inguruneetan beamforming-a eratzeko

koordinazioa sareen arteko interferentzia murriztera bideratuta dago.

Irrati kognitiboa. Irrati kognitiboan (Cognitive Radio, CR) oinarritutako komunikazioak espektra hobeto erabiltzeko aski ezagunak diren teknologiak dira. Hala ere, CR eta NOMA tekniken konbinazioak errendimendu orokorra hobetzea ekar lezake. Lehenik, [122]-n, CR sare handiak NOMA erabiliz ikertzen da. Zehazki, geometria estokastikoko eredu bat proposatzen da, bigarren mailako transmisore batekin konbinatuta, NOMA erabiltzaileekin komunikatzeko. Aurreko lanaren luzapen gisa, [123]-n NOMA-CR sare kooperatibo bat diseinatzen da, aldi berean birtransmisioak inplementatzen dituena. Gero, autore berberak sakonago aztertzen dituzte erabiltzaileen antolakuntza-eskemak, eta [124]-n helburu desberdinak dituzten bi aukera berri proposatzen dituzte, bata eraginkortasuna areagotzeko eta bestea erabiltzaileen artean ekitatea bermatzeko. Azkenik, erabiltzaileak taldekatzeko algoritmoen inpaktua [125]-n ebaluatzen da CR-NOMA sistematarako. Bereziki, hartzaile finkoek eta CR-NOMAk errendimenduan duten eragina aztertzen dute.

PHY segurtasuna. Gaur egun, haririk gabeko komunikazioak hainbat zibererasoren eraginpean daude eta, beraz, PHYn segurtasuna ematea gero eta garrantzitsuagoa da. Bereziki, PHY segurtasun-tekniketan NOMA erabiltzeak ohiko ikuspegi kriptografikoei segurtasun gehigarria eman liezaieke. PHYn segurtasuna emateko oso teknika ezaguna da zarata artifiziala (Artificial Noise, AN) erabiltzea. Adibidez, [126] lanean, sare bat proposatzen da, non estazio baseak antena bat edo gehiago izan ditzakeen, eta antena anitzen kasuan, AN sortzen da entzuketak saihesteko. Sekretu-probabilitatearen ebaluazio analitikoa ere ematen da. Antzeko azterlan bat ematen da [127]-n, non lehen mailako komunikazio-sareetat hartzen baita: birtransmisio bakar bat inplementatzen duen SISO-NOMA kooperatiboa ikusmiratzaile batekin. Egileek sarearen sekretua eteteko probabilitatea ezarri zuten Amplify-and-Forward (AF) eta Decode-and-Forward (DF) protokoloetarako. Ondoren, [128] lanean, sarearen azterketa zabalagoa eskaintzen da, NOMAn oinarritutako bi birtransmisio erabiltzen baitira eta ikusmiratzaile kopuru ezberdina hartzen baita kontuan. Komunikazioaren sekretua hobetzeko, birtransmisio konfidentzialeko informazio eta interferentzia-seinaleen artean aldatzen da. Horrez gain, [129] lanaren egileek interferentzia-seinaleen erabilera ere kontuan hartzen dute. Izan ere, sareko nodoei bi rol esleitzen zaizkie. Jatorrizko nodoek interferentzia seinaleak transmititu behar dituzte, eta birtransmisio nodoek, berriz, birtransmisio mezua. Azkenik, NOMArekin PHY segurtasuna emateko konbinatutako beste teknika bat antena igorlearen hautaketa (Transmit Antenna Selection, TAS) da. Hau da, MIMO sistemaren antena bat bakarrik erabiltzea informazioa emateko eta komunikazioaren kostua eta konplexutasuna murrizteko komunikazio aniztasuna mantentzen den

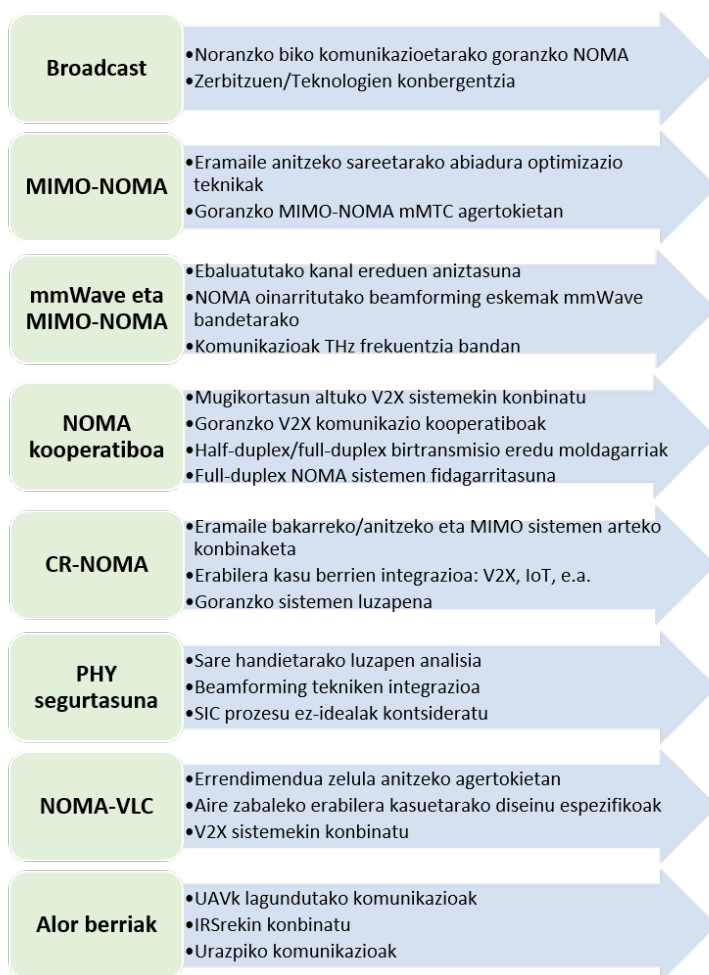
bitartean. Adibide garrantzitsu bat [130]-n aurki daiteke, non TASen ebaluazioak MIMO-NOMArekin konbinatuta etorkizun handiko emaitzak erakusten dituen.

VLC-NOMA. Argi ikusgarriaren komunikazioak (Visible Light Communications, VLC) ere kontuan hartu behar dira, etorkizun handiko aukerak baitira sarearen gaitasuna hobetzeko eta espektroaren kongestioa murrizteko. VLC teknologiarekin batera NOMA barneratzen duen lehen lanetako bat [131] da, non bi erabiltzaileen beheranzko lotura-sistema bat diseinatzen den eta ohiko OFDMA eskemekin alderatzen den. Emaitzek errendimendu hobea erakusten dute NOMA kasuan. Gero, erabiltzaileei kalitate onargarria emateko, [132]-ren egileek irabazi erlazioko potentzia esleitzeko (Gain Ratio Power Allocation, GRPA) teknika bat proposatzen dute, erabiltzaile bakoitzaren kanalaren momentuko kalitatea kontuan hartzen duena. [133]-n ere helburua gutxieneko kalitate-zerbitzua (Quality of Service, QoS) bermatzea beheranzko NOMAn da. Beraz, etete-probabilitateak eta zerbitzu oportunisten datuen abiaduraren adierazpena lortzen dituen QoS-a erakusten da. Gainera, [134]-n Chebyshev aurrekodegailua aurkezten da, kanal ez-linealetan MIMO-NOMAn errendimendua hobetzeko. VLCn ere aztertu den beste alderdi bat erabiltzaileen mugikortasuna da. Bereziki, [135]-ren egileek erabiltzailearen ausazko mugikortasuna aintzat hartzen dute eta QoS, etete-probabilitatea eta datuen abiadura-adierazpenak definitzen dituzte. Azkenik, kontzeptu-froga gisa, [136] lanean, NOMA-VLCren erabilera esperimentalki frogatzen da bi norabideko OFDMA sare bat erabiliz.

1.2.1.5 Garatzeke dauden gaiak

Nahiz eta, aurreko ataletan ikus daitekeen bezala, gaur egungo komunikazio sistemen errendimendua hobetzen duten NOMAn oinarritutako sistemen garapenean ahalegin handia egin den, oraindik ikertutako arloei lotutako hainbat ikerketa lerro daude. Zehazki, 1.7 irudiak, hainbat lanetan emandako jarraibideei jarraituz [55, 56, 57], NOMAn oinarritutako ikerketa nagusien laburpen bat erakusten du, ikerketa-arloen arabera antolatuta.

Lehenik eta behin, NOMAn arrakastarik handienetako bat irratidifusio bidezko komunikazioen teknologietan gertatu bazen ere (hau da, ATSC 3.0), erabiltzaileek eskatutako zerbitzuen etengabeko bilakaeraren ondorioz, NOMAn oinarritutako ikerketa-arlo berriak agertu dira. Adibidez, erabiltzaileen QoS-a edota esperientziaren kalitatea (Quality of Experience, QoE) hobetzeko, Hybrid Broadcast Broadband TV (HbbTV) bezalako zerbitzuak ezartzen ari dira, non erabiltzaileentzako goranzko lotura kanal bat beharrezkoa den. Hala ere, NOMAn



IRUDIA 1.7: NOMAren etorkizuneko ikerketa-arloak alor ezberdinetan antolatuta

oinarritutako goranzko lotura kanal hauen errendimendua ez da aztertu. Gainera, etorkizuneko broadcast komunikazioek zerbitzu eta teknologien konbergentzia bermatu beharko dute, eta horretarako teknologia gaitzaileak funtsezkoak izan daitezke.

Ikerketa-arlo espezifikoei dagokienez, MIMO-NOMAn, ikerketa-lan gehienak eramaile-bakarreko sareetara bideratuta daude. Beraz, datu tasaren optimizazioa eta datuen abiaduraren mugak sakonago aztertu behar dira eramaile anitzeko inguruneetan. Gainera, MIMO-NOMAren goranzko loturako kanala ingurune ultra dentsuetan ustiatu behar da (hau da, mMTC).

mmWave NOMA bandaren kasuan, lan gehienek LOS baldintzak

asumitzen dituzten, hartzaileak transmisoretik gertu egoten direlako. Hala ere, egia esan, zenbait egoerak kanal-baldintza desafiatzaileagoak ekar litzakete, eta horiek azter litezke. Orduan, etorkizuneko ikerketa-lan interesgarri bat izan liteke uhin milimetrikoko banden aplikazioetarako NOMAn oinarritutako beamforming-a eratzeko eskema espezifikoak konbinatzea edo diseinatzea. Azkenik, adituek aurreikusten dutenez, epe ertaineko komunikazioak THz maiztasun-bandetan inplementatu ahal izango lirake, eta, beraz, banda horien inplementazio-erronkak eta arazoak ikertu beharko lirake.

Komunikazio-kooperatiboi dagokienez, ikerketa-bide nagusi bi nabarmendu daitezke. Lehenengoa NOMA kooperatiboak erabilera-kasu berrietarako garatzea da, hala nola ibilgailutik ibilgailurako (Vehicle-to-Vehicle, V2V) edo V2X komunikazioak. Ildo horren barruan, NOMAn oinarritutako goranzko lotura-kanalaren definizioa eta errendimendua ere aztertu behar dira. Gero, bigarren norabidea full-duplex komunikazioetara bideratuta dago, lan gutxik diseinatu baitute kommutazio dinamikoa full-duplex eta half-duplex artean, sarearen baldintzen arabera. Gainera, fidagarritasuna handitzeari eta NOMAn oinarritutako full-duplex komunikazio optimoak garatzeko gaitasunari buruzko ikerketak erakargarria izan beharko luke.

NOMA kooperatiboan bezala, CR-NOMA sistemak beste teknologia batzuekin konbinatu behar dira, hala nola eramaile anitzeko komunikazioekin edo MIMO masiboarekin. Amaierako erabilera-kasuaren arabera, ikerketa-lerroak zabaldu litezke eskari handiko aplikazioak estaltzeko, V2X edo IoT sareak, esaterako. Azkenik, CR-NOMAn goranzko loturako eskemak ere sakon aztertu behar dira.

NOMA erabiliz PHY segurtasuna bermatzeko, lan gehienak sare txikietara mugatuta daude. Beraz, interesgarria litzateke sare handietan PHY segurtasun-teknikak aplikatzea. Gainera, segurtasun-tasa hobetzeko, NOMAn oinarritutako PHY segurtasuna beamforming-a prestatzeko teknikekin konbinatu ahal da. Azkenik, ia lan guztiek baldintza idealak asumitzen dituzte, hortaz, SIC inperfektuak dituzten komunikazioak aztertu beharko lirake.

Oro har, NOMA-VLC agertoki txikietan probatu da, eta zelula anitzeko agertokietan egungo irtenbideak probatzea merezi du. Ideia horri jarraituz, ikerketaren zatirik handienak barne-inguruneetan egin dira, eta, beraz, komunikazio-baldintzak ez dira kanpoko aplikazioetan bezain gogorak. Gainera, aplikazioaren irismena handitu liteke NOMA-VLC beste erabilera-kasu batzuekin (V2X sistemekin, adibidez).

Azkenik, aurretik aipatu ez diren arren, NOMA aplikatu ez den beste eremu berritzaile batzuk badirela, edo, behintzat, oso lan gutxi aurkeztu direla nabarmendu behar da. Adibidez, tripulaziorik

gabeko aire-ibilgailuen (Unmanned Aerial Vehicle, UAV) aplikazioak etorkizuneko komunikazio-eremu oparoenetako bat dira [137]. NOMA UAV sistemetan integratzeari buruzko atariko lan batzuk dauden arren [138], oraindik esploratu gabeko eremu erabakigarria da. Bestalde, gainazal islatzaile adimendunak (Intelligent Reflecting Surfaces, IRS) ezagunagoak bihurtzen ari dira azken urteotan [139, 140], eta NOMA-rekin batera erabiltzeak etorkizun handiko fidagarritasun-irabaziak ekar litzake [141]. Azkenik, itsaspeko komunikazioak etorkizuneko komunikazio-sistemetarako ikerketa-eremu erakargarri gisa nabarmendu behar dira [142, 143]. Ikerketa-ildo honek NOMA-n oinarritutako sistema akustikoentzako irtenbideak jorratu behar ditu.

1.2.2 RRM

1.2.2.1 Kontzeptu orokorrak

Multimedia-zerbitzu berrien eskaria gero eta handiagoa denez eta bete-beharreko baldintzak gero eta zorrotzagoak, RRM teknikak funtsezkoak dira sortuko den trafiko guztia behar bezala kudeatzeko. Zehazki, erabilera-kasu berriek proposatzen dituzten erabiltzaileen ahalmen, datu-abiadura edo dentsitate eskaera desafiatzaileak bermatzeko, baliabideen kudeaketa optimizatu behar da. Ildo horretan, zenbait adituren arabera [26, 144], RRM teknikak kritikoak izango dira epe laburrean, honako arrazoi hauengatik:

- *Trafiko-bolumena*: neurri handi batean, zerbitzuetarako etengabeko sarbidearen eta multimedia-edukiaren kontsumoaren igoeraren ondorioz, sarean zehar bidaiatzen duen trafiko-bolumena esponentzialki handituko da. Beraz, eskakizunek sare-arkitektura eskalagarria eta autokonfiguragarria eskatzen dute, baita irrati bidezko sarbide-teknologia (Radio Access Technology, RAT) ezberdinekin elkarri eragiteko beharra ere. Baldintza horiek direla-eta, irrati-baliabideen kudeaketa ezin hobea da.
- *Konektatutako ekipoa*: trafiko-bolumenarekin bezala, 5G inguruneetan sarera konektatutako gailuen kopurua 100 bider handiagoa izatea espero da [7]. Horregatik, ingurunera sartzeko mekanismoek erabiltzaile guztientzako gutxienezko baliabideen bermea kudeatzeko gai izan behar dute. Horretarako, behar berrietara egokitu beharreko modulu kritiko gisa aurkezten dira RRM teknikak.
- *Eskakizun eta ezaugarri sorta*: zerbitzuak etengabe eskuratzearen eta erabilgarri dauden erabilera-kasuak areagotzearen beste ondorio bat QoS eskakizun-sorta zabala da. Hau da, sareak aldi berean erabili

behar ditu oso datu-abiadura txikiko zerbitzuak (hau da, dozenaka kbps testu- eta ahots-aplikazioetarako) eta ahalmen-balio handietara bideratutako aplikazioak (hau da, dozenaka Mbps EA/EB bezalako aplikazioetarako). Gainera, zerbitzu mota bakoitza ezaugarri espezifikoetara lotuta egongo da, hala nola gehieneko latentziari, mugikortasun-ereduari edo seinalearen sendotasunari. Horregatik, RRM teknikak beharrezkoak izango dira trafiko-bolumen handiak eta oso ezaugarri desberdinak dituzten sareak behar bezala kudeatzeko.

Tradizionalki, RRM teknikak arrakastaz transmititutako informazio kantitatea maximizatzearekin lotu izan dira. Hala ere, aurretik azaldutako arazoak direla eta, hori ez da nahikoa etorkizuneko sareetan. Bereziki, RRM teknikak irratirako sarbide-sareko (Radio Access Network, RAN) baliabideen kudeaketan oinarritzen dira. Hala ere, estandar mugikorretan (hau da, 4G/5G), RRM modulua hainbat atazaren arduraduna da [26]. Hona hemen RRM tekniken funtzio garrantzitsuenak:

- *Baliabideen esleipena*: RRM moduluak eskuragarri dauden irratirako baliabideak partekatu behar ditu sarbidea eskatzen duten erabiltzaileen edo aplikazioen artean. Gainera, esleipen-prozesua ez da soilik erabiltzaileen eta transmisore nodoaren arteko zuzeneko loturarako; sare generikoetarako sarbidea eta backhaul seinaleak ere kudeatu behar dira. Baliabideak esleitzeko etapa sarearen hainbat parametroren arabera egokitu behar da, hala nola erabiltzaile-kopuruaren, erabilgarri dauden baliabideen edo kanalaren baldintzen arabera.
- *Paketeen programazioa*: sarearen kapazitate orokorra eta eraginkortasun espektrala zuzenean lotuta daude transmisio-denbora tarte (Transmission Time Interval, TTI) bakoitzean egindako paketeen programazio zuzenarekin [145]. Programazio-prozesua hainbat adierazleren arabera egiten da, hala nola CSI, erabiltzaileak eskatutako aplikazioetarako QoS betekizunak edo kanalaren egoeraren adierazlea (Channel Quality Indicator, CQI).
- *Loturaren egokitzapena*: jasotako datu-tasa eta zerbitzuen sendotasuna hobetzeko, loturaren egokitzapenak potentzia kontrolatzeko eta modulazio eta kodea egokitzeko (Adaptive Modulation Coding, AMC) mekanismoak ezartzen ditu. Gainera, potentziaren eta AMCren kudeaketa konbinatuak eta baliabideen esleipenaren kontrolak kanpoko interferentzien inpaktua edo seinaleak kanalean zehar jaso ditzakeen itzaltze efektuak murriztu ditzake.

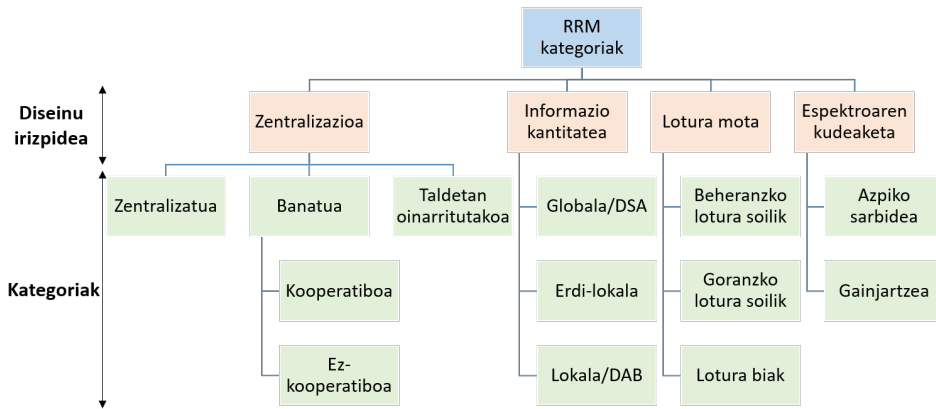
- *Onarpen kontrola eta transferentzia*: alde batetik, irrati bidezko onarpen-kontrolak erabakitzen du erabiltzaile bakoitzari sarerako sarbidea ematea, eskatutako baliabide-kopuruaren eta unean uneko eskuragarritasunaren arabera. Erabiltzaile batek sarerako sarbidea eskatzen duenean, beste erabiltzaile bat den edo aldameneko zelula bateko transferentzia batekoa den ere egiaztatzen da. Kasu honetan, RRM moduluak erabakitzen du sarerako sarbidea ematen duen eta behar diren baliabideen kopurua erabakitzen du, erabiltzailearen QoS eskakizunen arabera.

RRM kontzeptuak hainbat zeregin barne hartzen dituen arren, tesi honen ardatza baliabideak esleitzeko fasea da. Batetik, efizientzia espektrala etengabe hobetzearekin gehien lotzen den funtzioa delako, eta, bestetik, gainerako zereginak baliabideen kudeaketara bideratzen direlako. Beraz, hemendik aurrera, RRM eta baliabideen esleipena berdin erabiliko dira, eta RRM erabiltzen den guztietan, baliabideen esleipenari dagokio beti.

Arestian aipatu bezala, transmisoreak baliabideak esleitzeakoan, zenbait parametro, hala nola behar den banda-zabalera eta datu-tasa edo mugikortasun-eredua, kontuan hartu behar dira. Beraz, baliabideak esleitzeko prozesua errazteko, lan-esparru osoa bi azpiatazatan bana daiteke: espektroa esleitzea eta transmisio-parametroak zehaztea [146].

Alde batetik, lehenengo zeregina burutzeko espektroa kudeatzeko hainbat teknika eraginkortasunez aplikatu behar dira, erabiltzaileen QoS baldintzak eta eskaintako zerbitzuak betetzeko. Zehazki, espektroa esleitzeko lanak berezko hainbat erronka ditu. Adibidez, une bakoitzean eskura dagoen espektro kopurua zein den jakin behar du. Gero, baliabideak esleitzeko atazak erabaki behar du zein den espektro-zatirik onena une bakoitzean erabiltzaile bakoitzarentzat, eta sarbidea eta espektroaren partekatzea sinkronizatu behar du eskatzaile guztien artean. Izan ere, batzuetan (adibidez, konkurrentzia handiko inguruneetan), lehentasuna emateko erabakiak hartu behar dira sarerako sarbidea mugatzeko edo eskura dagoen espektro guztia partekatzeko. Azkenik, espektroaren kudeaketa eta erantzun-abiadura hobetzeko, ikasteko gaitasunak sar daitezke [147].

Bestalde, QoS eskaeraren arabera erabiltzaile bakoitza zerbitzatzeko, RRM etapak hainbat transmisio-parametroren balioa zehaztu behar du (adibidez, transmisio-potentzia edota MCS balioa). Aurreko kasuan bezala, zeregin honek ere bere erronka propioak ditu. Lehenik eta behin, RRM moduluak baliabideak ezagutu eta esleitu behar ditu, erabiltzaile bakoitzaren gehieneko interferentzia onargarriaren arabera. Parametro hau CQI transmisioarekin lotuta egon ohi da, erabiltzaileak kanalaren



IRUDIA 1.8: Irizpide ezberdinen arabera RRM tekniken sailkapena

baldintzen arabera deskodetu dezakeen MCS balio maximoa zehazten duena. Ondoren, transmisio-parametroak zehaztu behar dira gutxieneko QoS bat emateko, eta parametro horiek SNR balioak, gutxieneko datu-abiadurak edo gehieneko interferentzia onargarriak isla ditzakete, besteak beste. Beraz, RRMk eskakizun guztiak aldi berean erabili behar ditu, baita KPI desberdinekin lotuta badaude ere.

1.2.2.2 RRM tekniken taxonomia

Literaturan baliabideak esleitzeko teknika asko aurki daitezke, hainbat irizpidetan oinarrituta eta hainbat ingurutara bideratuta. Beraz, funtsezko irizpidearen arabera baliabideak esleitzeko teknikak hainbat modutan sailka daitezke [146, 148]. Atal honek RRM tekniken sailkapen ohikoenak aurkezten ditu, eta 1.8 irudian kategorien eta irizpideen laburpen bat erakusten da. Sailkapen bakoitza irizpide jakin bati dagokiona denez, RRM eskema bera hainbat modutan sailka daiteke.

Zentralizazio maila. Sailkapen-irizpide ohikoenetako bat zentralizazio maila da, eta hiru kategoria sortzen dira: zentralizatua, banatua eta taldetan oinarritua. Lehenik eta behin, zentralizatutako irrati baliabideak esleitzeko eskema sare batean oinarritzen da, non transmisorea nodo zentrala den, eta potentzia-kontrolaren eta espektroa esleitzeko erabakien ardura duen [149, 150]. Oro har, eskema horiek bi fasetako arkitektura inplementatzen dute. Lehenengo fasean, espektroaren egoera eta erabiltzaileen eskaerak biltzen dira. Gero, bigarren fasean, baliabideak esleitzeko erabakiak lehen fasean lortutako emaitzen arabera hartzen dira. Eskema horren abantaila nagusia nodo zentralak sare osoaren ikuspegi globala duela da eta, beraz, erraz lor ditzakeela optimizazio-helburuak.

Bestalde, eragozpen nagusia erabiltzaileen eta transmisio-nodoaren arteko mezu-trukeak eragindako seinaleztapen-gainkarga handia da. Gainera, arkitektura zentralizatuan, nodo zentralak baliabideak sarean sartutako nodo guztiei esleitzeko erabakia transmititzen die. Sare zabaletan, potentzia handiko esleipena behar da sarearen ertzeko erabiltzailearekin komunikatzeko. Gainera, difusio-komunikazioak huts egiten badu, sareko erabiltzaile bakar batek ere ez du esleipen-eguneraketa jasotzen. Bereziki, kategoria hau oso tipikoa da sare mugikorretan eta sentsore sare aplikazio batzuetan, hala nola monitorizazioa [151].

Aitzitik, banatutako baliabideak esleitzeko eskemak ez dira inolako nodo zentraletan oinarritzen. Kasu honetan, erabiltzaile bakoitza bere transmisio-erabakien arduraduna da [152, 153]. Bereziki, erabakiak sareko gainerako erabiltzaileekin lankidetzan edo modu autonomoan har daitezke. Bi kasuetan, eskema zentralizatuan baino azkarrago egokitzen dira aldaketak, ez baita berrelikadurarik behar. Gainera, arrazoi beragatik, gainkarga eta sareko trafikoa murrizten dira. Hala ere, banatutako eskemen desabantaila nagusia erabiltzaile bakoitzak bere baliabideak tokiko informazioaren arabera bakarrik esleitzea erabakitzen duela da, eta horrek eragin kaltegarria izan dezakeela gainerako erabiltzaileengan, errendimendua gutxitzen duelako edo erabiltzaileen arteko ekitatea murrizten duelako. Oro har, sare banatuak sare zelular espezifikoetara bideratu dira, hala nola ad-hoc sareetara, birtransmisioetan oinarritutako sareetara edo irrati kognitiboko sareetara.

Azkenik, zentralizazio mailak zehazten duen azken kategoria taldetan (edo klusterretan) oinarritutako arkitektura da. Kategoria honetan, sarea kluster ezberdinetan banatzen da, non kluster bakoitza talde nagusi (Cluster Head, CH) batek zuzentzen duen, informazioa bildu eta klusterraren esleipena kudeatzen duena [154, 155]. Abantailen artean, potentzia gutxi behar dela azpimarratu behar da, CHak sare osoaren zati bat maneiatu behar duelako eta, ondorioz, gainkarga txikiagoa izan behar duelako. Gainera, CH batean errore bat gertatzen denean, kluster horren erabiltzaileak gertuen dagoen CHari esleitu dakioke. Klusterretan oinarritutako eskemen eragozpenei dagokienez, adierazgarriena sare osoko transmisio-seinaleen kopurua handitzea da. Bereziki, arkitektura hau egokia da eskala handiko jauzi anitzeko sareetarako.

Informazio kantitatea. Gero, sarean partekatutako informazio kantitatea kontuan hartuz gero, balizko eskemak globaltzat (hau da, espektroarako sarbide dinamikoa edo Dynamic Spectrum Access DSA), lokaltzat (hau da, sarbide zuzenean edo Direct Access-Based, DAB) edo erdi-lokaltzat sailka daitezke. DSA eskemek sare osoaren informazioa behar dute errendimendu orokorra hobetuko duen esleipen-eskema bat zehazteko [156, 157]. Zalantzarik gabe, eskema horiek informazio

asko eskatzen dute eta, beraz, kostu konputazional handia eta latentzia handia asumitu behar dira informazio guztia administratzeko. Hala ere, sarearen errendimendua lan-puntu optimotik gertu dago. Eskema horiek praktikoak dira baliabideak esleitzen dituen entitatearen eta erabiltzaileen arteko sinkronizazio-tasa handia lortu behar den sareetan.

DSA ez bezala, DAB eskemak esleipen-prozesuan erabilitako informazioa transmisore-hartzaile parera mugatzen dela esan nahi du. Kasu honetan, erabiltzaile bakoitzari esleitutako baliabideak banaka negoziatzen dira entitate zentralarekin [158, 159]. Eskema horrek konplexutasun txikia behar du. Sarearen eraginkortasuna ere txikia da, eta, beraz, esleitzeko erabakia soluzio optimotik oso urrun egon daiteke. DAB esleipen-eskema lokalak eta eskari indibidualen araberrako transmisioak garatzeko garrantzitsua da.

DSA eta DAB artean irtenbide orekatua eskaintzeko, eskema erdi-lokalak hartu behar dira kontuan. Esleipen erdi-lokaleko eskemetan, informazioa sareko eremu txikietan baino ez dago eskuragarri [160, 161]. Beraz, konplexutasun- eta efizientzia-baldintzak orekatuta daude. Irtenbide hori egokia da sare heterogeneoetarako, non sare berean baldintza eta aplikazio oso desberdinak dituzten erabiltzaileak egon behar diren.

Lotura mota. Erreferentzia gisa lotura mota edo komunikazio-norantza hartuz gero, goranzko loturako, beheranzko loturako eta lotura mistoko eskemak bereiz daitezke. Lehenengo kasuan, goranzko lotura bakarrik esleitzeko eskemak behar dira, baldin eta informazioa erabiltzaileetatik transmisorerara baino ez badoa [162, 163]. Egitura honek gaitz txikia eta latentzia baxua dakartza, bereziki komunikazio asinkronoetan. Hala ere, eragozpen nagusia transmisio-potentzia mugatzea da, oro har, erabiltzaile mugikorrek bateriaz elikatzen baitira. Goranzko lotura baino ez duten eskemen adibide garrantzitsu bat, beren informazioa erdiko nodo batera transmititzen duten sensore-sareak dira.

Beheranzko lotura bakarrik duten eskemen kasuan, erabiltzaileak hartzaile pasiboak dira eta nodo zentralak bere gain hartzen du baliabideak esleitzeko erantzukizun osoa. Beheranzko lotura bakarrik duten eskemak ezartzean, errazagoa da espektroaren erabilera oso eraginkorra izatea, esleipen-prozesua nodo berean zentralizatuta baitago [164, 165]. Gainera, sinkronizazio-baldintzak malguagoak dira eskema horrekin. Aldiz, beheranzko loturako eskemek erabiltzaileen berrelikadura behar dute esleipen-prozesua gauzatzeko. Prozesu hori hainbat parametrotan oinarritu daiteke, hala nola kanalaren baldintzetan, transmisorerako distantzian edo gutxieneko datuen abiaduran. Beheranzko lotura bakarrik duten komunikazioen ohiko adibide bat, maisu-morroki arkitektura bat ezartzen duten sareak dira, non morroiek, maisuak emandako aginduak

betetzen dituzten.

Gero, beheranzko eta goranzko loturak esleitzeko eskemak konbinatu eta lotura bien esleipena aldi berean inplementatu daiteke [166, 167]. Zalantzarik gabe, bi esleipen plano dituzten eskemak plano bakarreko eskemak baino askoz eraginkorragoak dira (hau da, beheranzko edo goranzko lotura bakarrik). Hala ere, bi plano konfiguratu behar direnez, kostu konputazional eta konplexutasun handiagoa onartu behar da. Eskema horiek komunikazio-sistema mugikorren ohiko adibideak dira, non erabiltzaileek eta nodo zentralak elkarri eragin behar dioten. Full-duplex komunikazioen adierazgarriak ere badira, etorkizuneko komunikazio sistema askotarako aurreikusten direnak.

Espektroa kudeatzeko era. Azkenik, beste bereizketa bat egin daiteke espektroa kudeatzeko eraren arabera. Irizpide horrek esleipen-teknikak banatzen ditu azpiko sarbidean eta gainjarritako sarbidean. Lehen esleipen-eskemak esan nahi du espektroaren zati bat zarata-zoruaren azpian partekatzen dela, espektro zabalduko teknikak erabiliz [168, 169]. Azpiko sarbide eskemetan, hartzailearen konplexutasuna handitu egiten da, emandako seinaleak deskodetzeko. Aitzitik, azpiko sarbide eskemen onurak honako hauek dira: espektro zabalduko tekniken ondorioz transmisio-potentzia txikia behar dela eta espektroaren eraginkortasuna handitzen dela. Eskema horiek egokiak dira zerbitzu bakoitzak betekizun desberdinak dituen lehentasunetan oinarritutako komunikazio konbergenteetarako.

Bestalde, gainjartze-eskemetan haririk gabeko kanala eskuragarri dagoenean bakarrik egin daitezke transmisioak [170, 171]. Beraz, banda-zabalera osoan dauden baliabideak etengabe identifikatu behar dira. Gainjartze-eskemen onura nagusia transmisioa programatzeko behar den konplexutasun txikia eta gainerako transmisioei sortutako interferentzia txikia dira. Hala ere, onura horiek azpiko eskemekin lortutako espektroaren eraginkortasuna jaistean lortzen dira. Gainjartze-tekniken adibiderik ezagunena OFDMAn oinarritutako esleipen sistemak dira.

Amaitzeko, 1.7 taulak arestian aipatutako RRM kategorien laburpena erakusten du, diseinu-irizpide ezberdinen arabera. Taulan kategoria bakoitzaren ezaugarri nagusiak eta onura, eragozpen eta aplikazio adierazgarrienak nabarmentzen dira.

1.2.2.3 Optimizazio estrategiak

Tradizionalki, baliabideak kudeatzeko algoritmoen helburua sareak erabiltzaileei datu-abiadura handiagoak emateko duen gaitasuna maximizatzea izan da. Hala ere, erabilgarri dauden aplikazio askok gero eta eskakizun gehiago ezartzen dituztenez eta sarean zehar

TAULA 1.7: Diseinu-irizpide ezberdinen araberako RRM tekniken kategorien laburpena

Diseinu-irizpidea	Deskribapena	Kategoria	Abantaila	Desabantaila	Aplikazioak	Erreferentziak
Zentralizazioa	Sare-arkitektura motan eta erabakiak hartzeko erantzukizunean oinarrituta	Zentralizatua	Sare osoko ikuspegia. Optimizazio-helburuak lortzeko erraztasuna	Gainkarga handia. Potentzia handia. Akatsen kalteberatasuna	Sare mugikorrek eta sentso-sareak	[149] [150]
		Banatuak	Gainkarga txikia. Azkar egokitzea	Datu lokaletan oinarrituta. Ez bidezkoa	Ad-hoc eta bir-transmisio sareak	[152] [153]
		Taldetan oinarritutakoa	Potentzia txikia. Gainkarga txikia. Akatsen aurkako sendotasuna	Broadcast seinaleak handitzea	Eskala handiko jauzi anizteta sareak	[154] [155]
Informazio kantitateak	Partekatutako informazio kantitatean oinarritutakoa	Globala/DSA	Sare osoaren errendimendua hobetzea	Latentzia handitzea. Kostu konputazionala	Sinkronizazio handiko sareak	[156] [157]
		Erdi-lokala	Komplexutasun txikia. Irtenbide orekatua	Ez-optimoa	Sare heterogeneoak	[160] [161]
		Lokala/DAB	Komplexutasun txikia	Eraginkortasun txikia. Ez-optimoa	Eduki eskariaren araberako transmisio sareak	[158] [159]
Lotura mota	Datu-fluxuaren noranzkok kategorioa zehazten du	Goranzko lotura soilik	Gainkarga txikia. Latentzia baxua	Transmititutako potentzia limitatua	Sentsore-sareak	[162] [163]
		Beherezko lotura soilik	Eraginkortasun handia. Sinkronizazio erraza	Berrelikaduraren beharra	Maisu-morrori sareak	[164] [165]
		Lotura biak	Efizientzia espektral handia	Bi planoren kudeaketa. Komplexutasun handia	Komunikazio mugikorrek eta full-duplex komunikazioak	[166] [167]
Espektroaren kudeaketa	Espektroaren antolamenduaren araberako zehaztapena	Azpiko sarbidea	Transmisio-potentzia txikia. Eraginkortasun handia	Komplexutasun handia	Lehentasunetan oinarritutako komunikazioak	[168] [169]
		Gainjartzea	Komplexutasun txikia. Interferentzia txikia	Eraginkortasun txikia	OFDMAn oinarritutako sistemak	[170] [171]

garraiatutako datuak gero eta gehiago direnez, baliabideen eskasia gero eta nabariagoa da. Horregatik, baliabideen kudeaketarekin lotutako ikerketa-lan berriek irismena handitu dute eta optimizazio-parametro desberdinak proposatzen ari dira. Atal honen helburua gaur egungo optimizazio-parametro garrantzitsuenak aurkeztea da, lan esanguratsuenetako batzuekin batera.

Throughput. Baliabideak esleitzeko eskemetan gehien erabiltzen den optimizazio-metriketako bat throughput-a da, sareko erabiltzaile bakoitzari bidalitako datu-abiaduren batura gisa kalkulatzen dena. Throughput-a maximizatzen duen baliabideak esleitzeko teknikaren adibide bikain bat [172]-n erakusten da. Bertan, erabiltzaileen elkartze eta baliabideak esleitzeko eskema bat proposatzen da. Algoritmoa Mamdani motako logika lausoko kontrolagailu (Fuzzy Logic Controller, FLC) batean oinarritzen da. Kontrolagailu horrek erabiltzaileak eskatutako datu-

abiaduraren arabera sailkatzen ditu lehenik, eta erabiltzaile bakoitzari dagozkion baliabideak esleitzen dizkio. Emaitzek errendimendu hobea erakusten dute datuen abiadurari eta banda-zabaleraren erabilerari dagokienez, ikuspegi zuhur tipikoekin alderatuta. Irtenbide horren eragozpen nagusia sarearen karga-orekaren arazoa kontuan hartzen ez dela da, eta desoreka-egoera batek eskainitako throughput-a murriztea eragin dezakeela. Ondoren, [173]-ko egileek eskema oso bat definitzen dute, non eskainitako throughput-aren maximizazioa helburu nagusia den. Aldi berean, mailen arteko interferentzia eta transmititutako potentziaren muga hartzen dira kontuan. Esleipen eskema azpian dauden komunikazioetan oinarritzen da eta optimizazio arazoa Lagrange-ren deskonposizio dualaren metodoarekin ebazten da. Emaitzek konfigurazio optimoa oso iterazio gutxi onartuta lortzen dela adierazten dute. Hala ere, ez dira kontuan hartzen sarearen barruan sortutako interferentziak. [174]-n, baliabideen esleipenaren arazoak bideratzearekin batera egiten du aurre. Kasu honetan, baliabideen esleipena algoritmo estokastiko baten bidez egiten da, eta bideraketa, berriz, programazio linealeko konpongailu baten bidez. Diseinatutako metodoak erakutsi zuen elkarlan-prozesuak throughput, eraginkortasun espektrala eta efizientzia energetikoa hobetzen dituela. Azterketa honen desabantaila nagusia bideratze-erabakian inplikaturako latentzia ebaluatzen ez dela da.

Azkenik, baliabideak azpitaldeka esleitzea eta sarearen throughput-a maximizatzea helburu duen algoritmoen familia aipatzea merezi du [175, 93]. Lehenengo lanak erabiltzaileak taldeka banatzen dituen eta bakoitzaren konfigurazioa erabakitzen duen (hau da, MCS) algoritmo bat erakusten du. Bigarrenak, berriz, kudeaketa-logika berarekin jarraitzen du, baina baliabideak NOMA bidez kudeatzen ditu. Emaitzen arabera, azpitaldetan oinarriturako teknikek nabarmen hobetzen dute sarearen throughput-a. Hala ere, teknika honen eragozpen nagusia konfigurazio posibleen throughput-aren analisisian oinarritzen dela da, honek kostu konputazional altua suposatzen duelarik.

Efizientzia espektrala. Beste optimizazio-metrika zabalduenetako bat efizientzia espektrala da. Kasu honetan, espektro kantitate espezifiko baten barruan (hau da, bps/Hz) eman daitekeen gaitasuna adierazten du. [176]-ren egileek esleipen-eskema adierazgarri bat garatu dute, taldekatze-jokoaren algoritmo batean oinarrituta. Algoritmo horrek sortutako interferentziak ere kontuan hartzen ditu. Bi urratsetan banatuta dago; lehenik, grafoen teoria-jokoei jarraituz kudeatzen da taldea, eta, gero, talde bakoitzerako baliabideak enkanteko joko-mekanismo baten bidez esleitzen dira. Onura nagusia maiztasunak berrerabiltzearekin eta zelula txikien throughput-a moldatzeko sistemekin bateragarria dela da. Aitzitik, ez da kontuan hartzen erabiltzaileek eskatutako zerbitzu mota.

Ondoren, [177] lanaren egileek efizientzia espektralaren optimizazioa eta sare kooperatiba txikientzako energia-efizientzia konbinatzen dituzte. Zehazki, bi mekanismo garatzen dira: bata, interferentziak kudeatzeko, eta, bestea, trafikoa deskargatzeko. Emaitzen arabera, bi mekanismo horiek kooperatiboak ez diren eskemak gainditzen dituzte, espektroraginkortasunari eta energia-eraginkortasunari dagokienez. Hala ere, sare barruko interferentziak baino ez dira kontuan hartzen. Azken lana [178] artikuluan aurki daiteke, non baliabideen esleipena gune jakin baterako egiten den eta efizientzia espektrala eta energia-efizientzia aldi berean optimizatzeko diseinatuta dagoen. Baterako ebaluazioa egiteko, bilaketa bitarreko algoritmo bat diseinatzen da. Ebaluazioak erakusten du hainbat parametro etengabe aldatzen badira ere (adibidez, banda-zabalera, energia-kontsumoa edo erabiltzaile-dentsitatea), eraginkortasun espektrala eta efizientzia energetikoa epe laburretan hobetu daitezkeela diseinatutako algoritmoari jarraituz. Kasu honetan, alderdirik txarrena sarean nahitaez sortzen den galkarga da.

QoS/QoE. Erabiltzaileak jasotako zerbitzuarekin duen asebetetzea gaur egungo haririk gabeko komunikazioen adierazle garrantzitsuenetako bat da, eta, beraz, QoS/QoE parametroetan oinarritutako baliabideak esleitzeko eskemak kontuan hartu behar dira. Gai hau jorratzeko, [179]-n, sare heterogeneoetarako RATERako sarbide eta baliabideak esleitzeko teknika adimentsu bat diseinatzen da, agente anitzeko ikaskuntza-teknika batean oinarritutako QoS-a betetzen dela bermatzen duenak. Egileek RATERen hautaketa Nash Q-learning algoritmo batekin ebatzen dute, eta, ondoren, esleipena Monte Carlo Tree Search (MCTS) algoritmo batekin egiten da. Emaitzek RATERen hautaketa bilaketa kopuru txikiekin posiblea dela eta algoritmoaren esleipenak beste metodo tipiko batzuk gainditzen dituela erakusten dute. Eragozpen nagusia egonkortze-etapara iritsi aurretik kostu konputazional handia behar dela da. Ondoren, [180]-n, zerbitzuak blokeatzeko probabilitatea mugatzea da QoS bermatzea. Egileek Markoven ereduaren oinarritutako throughput-a maximizatzen duen hierarkia-baliabide moldagarria duen algoritmo bat definitzen dute. Emaitzen arabera, eredu moldagarriak ikuspegi estatikoek baino hobeto funtzionatzen du, baina hainbat iterazio eta kostu konputazional altuak behar dira azken konfigurazioa lortzeko. Azkenik, [181]-n, azpiko komunikazioetarako QoE erabiltzen da optimizazio-irizpide nagusitzat. Baliabideen esleipenaren arazoa konpontzeko, alde biko grafiko doitua erabiltzen duen algoritmo bat erabiltzen da. Emaitzek erakusten dutenez, gutxieneko QoE lortzen bada ere, energia eta ekitatea esleitzeko metrikak hobetu daitezke. Lanak ez du eskala handiko analisirik, piko-zelulen inguruneak bakarrik hartzen baitira kontuan.

Ekitatea. Seinalearen kalitate-adierazleez gain, ekitatea haririk gabeko

sareetan ere metrika garrantzitsua da. Adibidez, [182] lanean, helburua ekitate/throughput sistema orekatua lortzea da eta, horretarako, hainbat baliagarritasun-funtzio ponderatu erabiltzen dira. Emaitzek konpentsazio positiboak lor daitezkeela erabiltzaileen berrelkadura kontuan hartuz gero adierazten dute. Zalantzarik gabe, baldintza horrek sistemaren gainkarga areagotzen du. [183]-k, [182]-ren antzera, throughput eta ekitatearen arteko orekarako haztatuko baliagarritasun-funtzioetan oinarritutako algoritmoa erakusten du. Kasu honetan, lehenik eta behin, banda-zabalera erabilgarria zuzentasunez zatitzen da, eta, gero, baliagarritasun-funtzioak throughput balioa hobetzeko aplikatzen dira. Ikuspegi horren onura nagusiak trafiko/erabiltzaile eredu desberdinetara egokitzea eta eskalagarritasuna dira, sare handiagoekin erabil baitaiteke emaitzak okertu gabe. Hala ere, konfigurazio optimoak lortzeko behar den kostu konputazionala nahiko altua da. Azkenik, [76]-n azpitaldeen ikuspegi berezi bat erakusten da, non multicast azpitaldeen teknikak NOMA multiplexazioarekin konbinatzen diren murrizketa malguekin. Kasu honetan, proposatutako algoritmoetako batek ekitatea eta erabiltzaileen throughput-a maximizatzen ditu eta OMAN oinarritutako algoritmoek baino errendimendu hobea erakusten du. Hala ere, aurreko kasuetan bezala, kostu konputazional handia onartu behar da.

Interferentzien kudeaketa. Komunikazio-sistemak eraikitzean kontuan hartu beharreko beste alderdi bat interferentzien kudeaketa da. Erabiltzaile/nodo batek bere sarean sortzen dituen interferentziak (hau da, maila berekoak) edo ondoko sarean sortzen diren interferentziak (hau da, mailen artekoak) izan daitezke. Ildo horretan, [184]-n, interferentziak baliabideen esleipenarekin batera kudeatzen dira ingurune desberdinetako hiru mailatako arkitektura baterako (hau da, makrozelula, zelula txikia eta gailutik gailura edo Device-to-Device, D2D). Proposatutako algoritmoak banda-zabalera azpibandetan banatzen du, eta throughput- eta interferentzia-murrizketak jarraitzen ditu baliabideak esleitzeko. Interferentziak saihesteko emaitzak bikainak izan arren, algoritmoaren prozesatze-denbora altuegia da benetako inguruneetarako (10 segundo). Antzeko filosofia jarraituz, [185]-n frekuentzia zatika berrerabiltzeko (fractional frequency reuse, FFR) metodo bat proposatzen da, sare osoa hiru sektore eta hiru geruzatan eta banda-zabalera osoa zazpi azpi-bandatan banatzen duena. Gero, azpi-banden esleipena hainbat tamainatako sareen interferentzia- eta throughput-murrizketen arabera egiten da. Emaitzek throughput balio altua erakusten dute, interferentzia onargarriarekin. Zoritzarrez, beharrezkoa den kostu konputazionala nahiko altua da hiru mailen sektorizazioaren ondorioz. Interferentziarekin lotutako beste ikuspegi bat [186]-n aurki daiteke, hiru geruzatako sare heterogeneoa proposatzen duena. Kasu honetan,

algoritmoa bi etapatan banatzen da: lehengoa, azpi-kanalak esleitzea eta potentzia kontrolatzea, eta bigarrena, interferentziak kudeatzea. Lanak funtzio logaritmikoak eta taldekatze-teknikak konbinatzen ditu. Interferentzien inpaktua erabat banatutako inguruneetan ere ezabatzen den arren, energia-kontsumoaren errendimenduak okerrera egiten du. Interferentziak kudeatzera bideratutako azken lana [187] artikuluan aurkezten da. Bertan interferentziak koordinatzeko mekanismo bat aurkezten da, energia aurrezteko ikuskapenarekin batera. Egileek Markoven eredian oinarritutako algoritmo bat erabiltzen dute sarearen egungo eta etorkizuneko karga egoera eta QoS berrelikaduran oinarrituta. Emaitzek adierazten dute interferentzien inpaktua degradatu egin daitekeela eta, aldi berean, QoS hobekuntzak lor daitezkeela.

Eraginkortasun energetikoa. Kontuan hartuko den azken optimizazio-metrika eraginkortasun energetikoa da, oso garrantzitsua izan baitaiteke haririk gabeko etorkizuneko komunikazio-sareetan. Alde batetik, [188] lanean, algoritmo hungariarren eta helburu anitzeko haztatutako metodoen konbinazio bat proposatzen da D2D sareen eraginkortasun energetikoa optimizatzeke, gutxienezko QoS balioak bermatzen diren bitartean. Lan honetatik ateratako ondorio nagusia benetako blokeo-efektuak kontuan hartzen badira ere, erabiltzaileen arteko ekitatea ez dela kontuan hartzen da. Bestalde, eraginkortasun energetikoaren analisi desberdina egiten da [189]-n. Kasu honetan, optimizazioaren helburua batuketa haztatutako eraginkortasun energetikoa maximizatzea da, eta lehen mailako hurbilketa-algoritmo iteratibo bati jarraituz egiten da. Ebaluazioak optimizazio-metrikak bost iterazio baino gutxiagotan hobetu daitezkeela erakusten du. Ikuspegi horren eragozpen nagusia esleipena ez dela guztiz bidezkoa da. Azkenik, [190] lanaren egileek eraginkortasun energetikoa eta eraginkortasun espektralaren optimizazioa konbinatzen dituzte NOMA teknikekin. Kasu honetan, sareko bat-bateko baldintzen arabera pisu kontrolagarriko sistema bat diseinatzen da. Nabarmentzekoa da algoritmo horiek OMA teknikak gainditzen dituztela energia-eraginkortasunari eta espektroraginkortasunari dagokienez, konbergentzia azkarrarekin. Hala ere, ezarpen-kostua eskuraezina izan daiteke hartzaileen SIC modulua dela eta.

Amaitzeko, 1.8 taulak atal honetan aurkeztutako lanen laburpena erakusten du, optimizazio-helburuen arabera. Taulan erreferentzia bakoitzaren ezaugarri nagusiak eta ahulezia adierazgarrienak nabarmentzen dira.

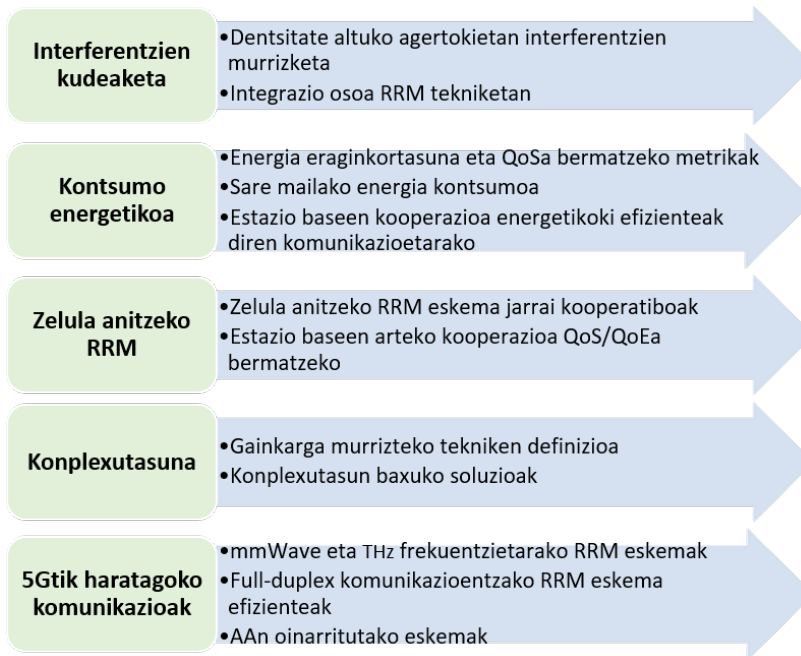
TAULA 1.8: RRM optimizazio-metrika ezberdinekin aztertutako lanen laburpena

Erref	Metrika nagusia(k)	Bigarren mailako metrika(k)	Deskribapena	Ahulezia(k)
[172]	Throughput	Bat ere ez	Erabiltzaileak elkartzeko eta FLCn oinarritutako baliabideak esleitzeko bi urratseko eskema	Sarearen karga-balantzea ez da kontuan hartzen
[173]		Interferentzien kudeaketa eta transmititutako potentzia	Lagrangeren banaketa dualaren metodoan oinarritutako azpiko komunikazio-sistema	Maila bereko interferentziak ez dira kontuan hartzen
[174]		Efizientzia espektrala eta eraginkortasun energetikoa	Bideraketa eta baliabideen esleipena batera optimizatu	Bideraketaren latentzia ez da kontuan hartzen
[175]		Bat ere ez	Erabiltzaileak azpitaldeetan banatzen dira eta azpitaldeen konfigurazioa optimizatuta dago	Kostu konputazional handia
[93]		Bat ere ez	NOMA teknikak erabiltzen dira azpi-taldeen eraketa eta optimizaziorako	Kostu konputazional handia
[176]	Efizientzia espektrala	Interferentzien kudeaketa	Jokoen teoria jarraitzen duen klusterretan oinarritutako algoritmoa	Erabiltzaileen QoS-a ez da kontuan hartzen
[177]	Efizientzia espektrala eta eraginkortasun energetikoa	Interferentzien kudeaketa	Bi mekanismo garatzen dira, interferentzia-lerrokadurari eta trafikoaren deskargari jarraituz	Sareen arteko interferentziak ez dira kontuan hartzen
[178]		Interferentzien kudeaketa eta ekitatea	Bilaketa bitarrean oinarritutako optimizazio bikoitza	Gainkarga handia
[179]	QoS	Bat ere ez	Ikaskuntza-teknika batean oinarritutako RATen sarbiderako eta baliabideak esleitzeko teknika.	Kostu konputazional handia
[180]		Throughput	Markoven ereduaren oinarritutako baliabide esleipen moldagarri hierarkikoa	Kostu konputazional handia
[181]	QoS	Ekitatea eta esleipen potentzia	Alde biko grafiko doituaz azpiko komunikazioetarako	Soilik piko-zelula kontuan hartzen dira
[182]	Ekitatea eta throughput	Bat ere ez	Baliagarritasun-funtzio ponderatuak baliagarriak diren konpromisoak lortzeko	Gainkarga handia
[183]		Bat ere ez	Banda-zabaleraren banaketa eta baliagarritasun-funtzioen konbinazioa	Kostu konputazional handia
[76]		Bat ere ez	NOMA oinarritutako taldekatze algoritmoak multicast zerbitzuetarako	Kostu konputazional handia
[184]	Interferentzien kudeaketa and throughput	Bat ere ez	Banda-zabaleraren banaketa eta murrizketen arabera esleipena	Prozesamendu denbora luzea
[185]		Bat ere ez	Sarea hiru sektore eta hiru geruzatan eta banda-zabalerara osoa zappi azpi-bandatan banatzen duen FFR metodoa	Kostu konputazional handia
[186]		Energia kontsumoa	Funtzio logaritmikoak eta klustering teknikan dituen etapa biko algoritmoa	Energia kontsumo handia
[187]	Interferentzien kudeaketa and QoS	Energia erreserbak	Sarearen kargan eta QoS berrelikaduran oinarritutako Markov modeloa	Gainkarga handia
[188]	Efizientzia energetikoa and QoS	Bat ere ez	Algoritmo hungariarra helburu anitzeko metodo haztatu-arekin konbinatua D2D sareetarako	Ekitatea ez dago bermatuta
[189]	Efizientzia energetikoa	Efizientzia espektrala	Lehen ordenako hurbilketa-algoritmo iteratiboa	Ekitatea ez dago bermatuta
[190]	Efizientzia energetikoa eta efizientzia espektrala	QoS	Sarearen bat-bateko baldintzen arabera diseinatutako pisu kontrolagarriko sistema	Kostu konputazional handia

1.2.2.4 Garatzeke dauden gaiak

Nahiz eta, aurreko ataletan ikus daitekeen bezala, baliabide irratielektrikoen kudeaketa eraginkorraren arloan asko aurreratu den eta etorkizun handiko proposamenak aurkeztu diren, oraindik ere hainbat arlotan jarri behar da arreta. Beraz, aurretik azaldutakoa eta beste aditu batzuek egindako azterketak erreferentziatzat hartuta [26, 144, 146, 148, 191], atal honek RRM eskemen inguruko etorkizuneko ikerketa-ildo garrantzitsuenak aurkezten ditu. 1.9 irudiak arloka antolatutako nabarmendu beharreko lerroen laburpena erakusten du.

Lehenik eta behin, interferentzien kudeaketa nabarmendu behar da. Haririk gabeko sareen etorkizuneko joerak erabiltzaile-dentsitate handia hartu behar duten sare txikiak (hau da, piko-zelulak edo femtozelulak) inplementatzea ekarriko duela kontuan hartuta, hartzaileentzat



IRUDIA 1.9: RRM eskemen etorkizuneko ikerketa-lerroak

arriskutsuak izan daitezkeen interferentziak esponentzialki hazten dira. Beraz, ingurune ultra dentsoekin bateragarriak diren interferentziak kudeatzeko sistemak diseinatu behar dira. Gainera, sare bakoitzaren nodo igorleak kudeatu beharko dituen zerbitzuak askotarikoak izango direnez, interferentzien kudeaketa erabat integratuta egon behar da RRM eskemekin. Bestela esanda, etorkizuneko RRM eskemetarako, interferentziaren kudeaketa QoS edo eraginkortasun espektrala bermatzea bezain garrantzitsua izango da.

5G/6G ekosistemaren parte izatea espero den gailu motari dagokionez, bateria-gailuak (telefono mugikorak, tabletak, sentsoreak edo IoT gailuak) oso garrantzitsuak izango direla uste da. Horregatik, epe-laburrean energiarekin lotutako parametroak kritikoak izango dira. Beraz, energia-eraginkortasuna funtsezko optimizazio-helburutzat hartu behar da, eta QoS-a bermatzen duten eskemekin konbinatu behar da. Gainera, sareko energia-kontsumoa, oro har, murriztu egin behar da, eta, helburu horrekin, hainbat erakunde 5G ekosisteman teknologia ekologikoak integratzeko presioa egiten ari dira. Horrez gain, oro har, energia-eraginkortasuna zelula bakar batean aztertzen da, eta zelula-anitzeko eskemak, berriz, ez dira kontuan hartzen. Bereziki, ikerketa-ildo interesgarri bat estazio baseen arteko lankidetzari ahalbidetuko duten RRM eskemak diseinatzea izango da, energia-eraginkortasuna handitzeko.

Azken ideia horren ildotik, eta sare heterogeneoek laster izango duten garrantziari dagokionez, aldi berean sare ugari kudeatzen dituzten RRM eskemak funtsezkoak izango dira. Etorkizuneko sareen tamaina txikia dela eta, erabiltzaile asko ez dira sare berari lotuta egongo denbora luzez, ezta teknologia espezifiko bati ere. Beraz, ikerketa-jarduera gehiago egin behar dira RRM eskema berriak diseinatzeko, erabiltzaileentzako sare-baliabide ugari arazorik gabe administratzeko. Izan ere, estazio baseen arteko lankidetzak, baita eduki desberdinak ematen dituzten edo teknologia desberdinetan oinarritzen diren estazio baseak ere (adibidez, 5G eta WiFi), erabiltzaileen QoS/QoEa bermatzeko mekanismo gisa oinarritu behar da, zelula anitz eraginkortasunez kudeatzen duten RRM eskemak erabiliz.

Etorkizuneko ikerketa-ildoetan landu beharreko beste gai bat konplexutasuna da. Zehazki, konplexutasunaren gaitik sortzen dira bi ildo nagusi: sistemaren konplexutasuna eta kostu konputazionala. Lehenengo kasuan, erabiltzaileen berrelikadurarekin sortutako seinalearen gainkarga murriztea funtsezkoa izango da, batez ere dentsitate altuko inguruneetan. Beraz, gainkarga gutxi behar duten seinaleetan oinarritutako RRM teknika berriak definitzea interesgarria izango da etorkizuneko inplementazioak errazteko. Bestalde, kostu konputazionalaren murrizketak haririk gabeko etorkizuneko sareetan egongo diren erabiltzaile-motarekin lotura estua du. Etorkizuneko sareek ez dute kostu konputazional handirik onartuko edo ez dira bateragarriak izango kostu konputazionalaren ondoriozko latentzia-gehikuntzarekin. Horregatik, konplexutasun baxuko konponbideetan ikerketa handiagoa egin behar da.

Azkenik, RRM eskemek 5Gtik haratagoko komunikazioetarako proposatzen diren erabilera kasu desafiatzaileen eskakizunak bete behar dituztela aipatu behar da. Adibidez, mmWave bandetan eta THz frekuentzia bandetan 6G ezartzea espero da. Zalantzarik gabe, THz komunikazioek egungo RRM eskemetan kontuan hartzen ez diren berezko erronka batzuk dituzte, hala nola galera handiak, oztopoekiko zaugarritasuna edo aldakortasun handia. Beraz, RRM proposamen berriek frekuentzia-banda altuenen eskakizunekin bat etorri behar dute. Beste erabilera kasu garrantzitsu bat full-duplex komunikazioak dira, eraginkortasun espektrala nabarmen handitzea espero baita. Hala ere, full-duplex komunikazioetarako RRM teknikak oraindik ez dira sakon ikertu. Azkenik, RRM eskemak AA bezalako teknika gehigarriekin indartu litezke. Lan batzuek AA oinarri duten RRM eskemak proposatu dituzten arren ([192, 193, 194, 195]), ez dago optimizazio helburu edo erabilera kasu ezberdinen azterketa sakonik.

1.3 Hipotesiak eta helburuak

1.3.1 Helburuak

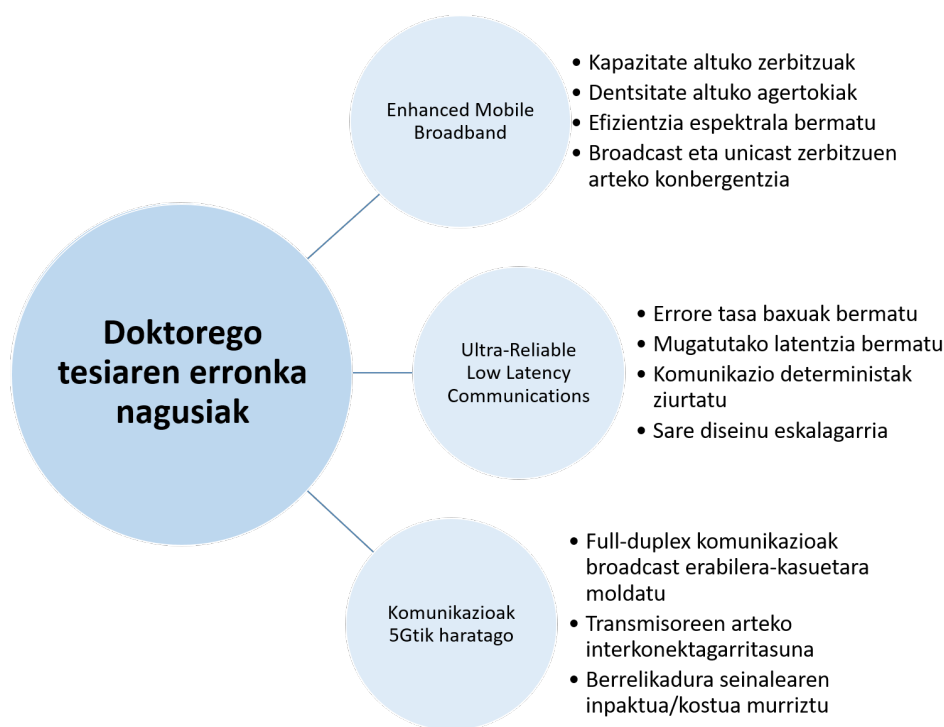
Tesi hau lau erabileretatik hirutan zentratzen da: eMBB, URLLC eta 5Gtik haratagoko komunikazioak. Lehenik eta behin, kontuan izan behar da eMBBk entretenimendu- eta banaketa-zerbitzu tradizionalen erabilera irudikatzen duela, non ohiko komunikazio-sistemen PHYak Shannon-en mugatik oso gertu funtzionatzen duen. Beraz, goiko geruzako soluzio berriak diseinatzeko eta integratzeko beharrak erronka zirraragarria planteatzen du.

Bestalde, URLLCk, komunikazio modernoek eta sendoenak sektore industrial tradizionalenarekin konbinatzean, erronka hau dakar: ohiko kabledun komunikazioak haririk gabeko sistemekin ordeztea errendimendua txarrera egin gabe. Gainera, URLLC bereziki interesgarria da tesia aurkezten den eremu geografikorako; izan ere, Euskal Herria industria-jardueraren eremu garrantzitsu gisa nabarmendu izan da historikoki. Ondorioz, azterketak eragin nabarmena izan dezake inguruko enpresetan. Azkenik, 5Gtik haratagoko komunikazioak ikerkuntzaren abangoardian lan egitea dakar, eta hori erronka handia da eta motibazio pizgarri pertsonala tesia garatzerakoan.

Tesian jorratu beharreko erabilera-kasuak definitu ondoren, kasu bakoitzarentzako helburuak honela definitzen dira:

- **1. Helburua:** NOMAn oinarritutako PHY/MAC egitura eta RRM algoritmo berriak proposatu, diseinatu eta ebaluatzea, eMBB inguruneetan broadcast zerbitzuak eskaintzeko, zerbitzuen ahalmena, kalitatea eta zerbitzatutako erabiltzaile kopurua handitzeko.
- **2. Helburua:** NOMAn oinarritutako PHY/MAC egitura eta RRM algoritmo berriak proposatu, diseinatu eta ebaluatzea, URLLC inguruneetako komunikazio kritikoek fidagarritasun errendimendua hobetzeko, latentzia arriskuan jarri gabe.
- **3. Helburua:** Ohiko irrati-difusioko sistemen inguruneetan full-duplex komunikazioak inplementatzeko beharrezkoak diren teknikak eta teknologiak proposatzea, diseinatzea eta ebaluatzea, frekuentzia-banda berean zerbitzu berriak txertatzeko, hala nola dorreen arteko komunikazioak.

Hala ere, aipatutako helburu bakoitza betetzeko, erronka teknologiko batzuei aurre egin behar zaie eta soluzioak proposatu behar dira. 1.10 irudiak tesi honetan integratutako erabilera-kasu bakoitzarekin lotutako erronken laburpena erakusten du.



IRUDIA 1.10: Tesiaren helburuekin lotutako erronka nagusiak.

Alde batetik, eMBB inguruneetarako diseinatutako komunikazio-sistemek egungo komunikazio-estandarren espektro-eraginkortasuna hobetu behar dute. Kodifikazioan eta modulazioan izandako azken aurrerapenen ondorioz, egungo komunikazio sistemak Shannon-en mugatik oso gertu daude. Gainera, eMBBn, komunikazio-sistemek garrantzitsuak izan behar dute erabiltzaileen dentsitatea oso handia den inguruneetarako, eta horrek esan nahi du eskaintako gaitasunak handiagoa izan behar duela. Azkenik, erabiltzaileek eskatutako zerbitzuen ezaugarriak direla eta, broadcast komunikazioek ezin dituzte unicast komunikazioak guztiz ordezkatu; beraz, broadcast eta unicast zerbitzuen arteko konbergentzia ahalik eta modu eraginkorrean bermatu behar da.

Bestalde, URLLC inguruneei egindako ekarpenak eMBBren erronken aldean erabat desberdinak dira. Adibidez, ingurune kritikoetako komunikazioak deterministak izan behar dira, eta, beraz, proposatutako MAC egiturek bermatu behar dute datu-paketeak modu deterministan jasotzea, bai eta latenzia-balio mugatuak izatea ere (hau da, 1-10 ms artekoak, erabilera-kasuaren arabera) [196]. Gainera, industriak erabiltzen duen KPI nagusietako bat galdutako paketeen proportzioa da,

gaur egun 10^{-6} - 10^{-9} inguruan kokatzen dena aplikazioaren arabera. Beraz, proposatutako sistemen errore-tasak maila horren barruan daudela bermatu behar da, industrian aplikatu ahal izateko. Hala ere, akatsen aurka babesteko eta galdutako datuak berreskuratzeko teknika gehienek latentzia handiagoa ekartzen dute, eta hori beste parametro kritiko bat da. Hori dela eta, proposatutako teknikek gehieneko latentzia mugatua izango dela bermatu behar dute, erabilera-kasuak ezarritako baldintzen barruan. Azkenik, URLLC etengabe garatzen ari den ingurunea denez, proposatutako diseinuek eskalagarriak izan behar dute.

Azkenik, broadcast transmisio-inguruneetan full-duplex komunikazioak ahalbidetzen dituzten teknika berrien diseinuak erronka berriak planteatzen ditu etorkizuneko 6G komunikazioetarako. Lehenik eta behin, nabarmendu behar da beste aplikazio batzuetarako (Wi-Fi edo 4G) full-duplex komunikazioak ikertu badira ere, 5G/6G aplikazioetarako berrikuntza bat direla. Beraz, lehen erronka beste aplikazio batzuetarako jada erabilitako tekniken artean, broadcast inguruneetarako aplikagarriak direnak aukeratzea da. Beharrezkoa bada, erabilera-kasu berrira egokitze beharrezkoak diren aldaketak diseinatu eta aplikatu behar dira. Ondoren, bermatu behar da berrelikadura seinalearen efektua behar bezala ezeztatu daitekeela. Beraz, seinalea ezeztatze arkitektura definitu beharko da. Azkenik, transmisio-zentroak elkarrekin konektatzeko behar den komunikazio-eskema definitzea proiektuaren beste erronka bat da.

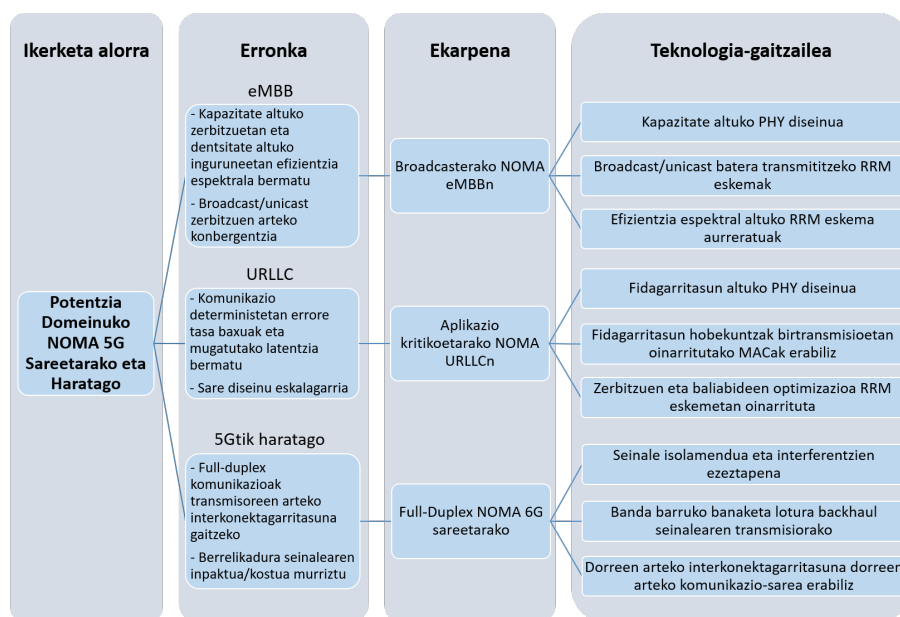
1.3.2 Ekarpinak

Tesi honen ikerketa arlo nagusia 5G ekosistema eta haratago osatzen duten sareetarako potentziaren eremuko NOMA aplikazio berrien diseinuan eta ebaluazioan oinarritzen da. 1.11 irudian erakusten den bezala, hiru dira tesi honetan jorratu diren ikerketa-arlo nagusiak: enhanced Mobile Broadband komunikazioak, Ultra-Reliable Low Latency Communications eta 5Gtik haratagoko komunikazioak.

Hurrengo paragrafoetan, helburu bakoitzaren ikerketa-erronkei lotutako ekarpenaren ezaugarriak deskribatzen dira (ikus 1.11).

1. Ekarpina: Broadcasterako NOMA eMBBn

eMBB 5Gren erabilera-kasu bat da, eta informazio eta entretenimendu aplikazio tradizionalak eta multimedia-kasu berritzaileak konbinatzen ditu, hala nola EA edo 3D bideo-transmisioa. Multimedia-aplikazio berriek sareak eskaintako ahalmena handitzea eskatzen dute, eta, erabiltzaileen eskaerei erantzuteko, NOMA proposatzen da broadcast/multicast gaitzaile gisa. C1 ekarpina 1. helburua betetzera bideratuta



IRUDIA 1.11: Tesiaren ekarpenen irudikapena.

dago (ikus 1.3).

Tesi honen helburuetako bat ohiko TDMA sistemek baino gaitasun tasa altuagoak ematen dituen NOMAn oinarritutako 5G PHY geruza bat diseinatzea da. Aldi berean, broadcast eta unicast zerbitzuen baterako existentziak multiplexazio-eskema egoki baten diseinua behar du. Gainera, sarearen eraginkortasun espektrala handitzeko, RRM eskemak ere hartzen dira kontuan. Alderdi honetan, NOMAn oinarritutako RRM eskema ezberdinak diseinatu eta ebaluatzen dira. Azkenik, etorkizuneko erabilera-kasuak jorratzen dira, hala nola multicast zerbitzuak azpitaldetan batzeko teknikak eta dentsitate handiko sareak mmWave bandetan.

Emaitzen arabera, NOMA egungo 5G estandarrean sartzeak espektroari eraginkortasun handia ematen dio, eta horrek transmisio-ahalmena handitu, sarean zerbitzatutako erabiltzaileen kopurua handitu edo zerbitzu sendoagoak eman ditzake.

C1 ekarpenarekin lotutako argitalpenak honako hauek dira:

- E. Iradier, J. Montalban, D. Romero, Y. Wu, L. Zhang eta W. Li, "NOMA based 5G NR for PTM Communications," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Hego Korea, 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971856.

- E. Iradier et al., "Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 503-514, Ekaina 2020, doi: 10.1109/TBC.2020.2981759.
- E. Iradier et al., "Broadcast/Unicast Convergence in NOMA-based 5G: a RRM Optimization Algorithm," 2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Paris, Frantzia, 2020, pp. 1-6, doi: 10.1109/BMSB49480.2020.9379805.
- E. Iradier et al., "Non-Orthogonal Multiple Access and Subgrouping for Improved Resource Allocation in Multicast 5G NR," *Digital Communications and Networks* aldizkarira bidalita.
- E. Iradier et al., "Advanced NOMA-based RRM Schemes for 5G mmWave Bands," *IEEE Transactions on Broadcasting* aldizkarira bidalita.

2. Ekarpena: Aplikazio kritikoetarako NOMA URLLCn

URLLCren ezaugarri nagusiak paketeen errore-tasa oso baxua, latentzia-balio baxu eta mugatuak eta komunikazio deterministak dira. Kasu honetan, NOMA sistemek ematen duten eraginkortasun espektralaren irabazia egungo URLLC aplikazioekin konbinatuta erabil liteke, ingurune hauen baldintza zorrotzei aurre egiteko. C2 ekarpena 2. helburua betetzera bideratuta dago (ikusi 1.3).

Alde batetik, tesi honen helburuetako bat kodifikazio eta deskodifikazio etapan NOMA barne hartzen duten PHY partikularrak diseinatzea da eta, bestetik, birtransmisioetan oinarritutako MAC geruzak ebaluatzea fidagarritasun orokorra handitzeko. Gainera, espektrο-baliabideen erabilera zuzen eta eraginkorra ere funtsezkoa da URLLC inguruneetan. Orduan, tesi honek hainbat RRM algoritmo aztertzen ditu irrati baliabideen erabilera hobetzeko.

Emaitzen arabera, NOMA URLLC sistemetan erabiltzeak komunikazioen fidagarritasuna hobetzen du. Birtransmisio-eskemekin konbinatuz gero, irabaziak paketeen errore-tasak zenbait magnitude-ordenatan murriztea dakar.

C2 ekarpenarekin lotutako argitalpenak honako hauek dira:

- E. Iradier, J. Montalban, L. Fanari, P. Angueira, O. Seijo eta I. Val, "NOMA-based 802.11n for Broadcasting Multimedia Content in Factory Automation Environments," 2019 IEEE International Symposium on Broadband Multimedia Systems and

- Broadcasting (BMSB), Jeju, Hego Korea, 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971844.
- E. Iradier, J. Montalban, L. Fanari eta P. Angueira, "On the Use of Spatial Diversity under Highly Challenging Channels for Ultra Reliable Communications," 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Espainia, 2019, pp. 200-207, doi: 10.1109/ETFA.2019.8869055.
 - E. Iradier et al., "Analysis of NOMA-Based Retransmission Schemes for Factory Automation Applications," IEEE Access, vol. 9, pp. 29541-29554, 2021, doi: 10.1109/ACCESS.2021.3059069.
 - J. Montalban, E. Iradier, P. Angueira, O. Seijo eta I. Val, "NOMA-Based 802.11n for Industrial Automation," IEEE Access, vol. 8, pp. 168546-168557, 2020, doi: 10.1109/ACCESS.2020.3023275.
 - E. Iradier et al., "Throughput, Capacity and Latency Analysis of P-NOMA RRM Schemes in 5G URLLC," Multimedia Tools and Applications aldizkarian argitaratzeko onartua.
 - E. Iradier eta J. Montalban, "Komunikazioak 4.0 Industrian," Elhuyar Aldizkarian argitaratzeko onartua.

3. Ekarpena: Full-duplex NOMA 6G sareetarako

Nahiz eta 5Gk aldaketa handia ekarri du egungo komunikazio-sistemetan, zenbait baldintza ez dira bete, hala nola ms-etatik bererako latentzia izatea edo eraginkortasun espektrala hobetzea. Izan ere, azken desabantaila hori hobetzeko, NOMA oinarritutako full-duplex komunikazioek beharrezko hobekuntza eman lezakete espektroraginkortasunean, zerbitzua 5Gtik haratago ezartzeko. C3 ekarpena 3. helburua betetzera bideratuta dago (ikusi 1.3).

Bereziki, tesi honek NOMA erabiltzen duen full-duplex arkitektura oso batekin lotutako diseinua eta erronkak aztertzen ditu, transmisio-eraketa eta backhaul datuak frekuentzia-banda berean konbinatzeko. Gainera, oinarritzko aplikaziotik abiatuta, transmisio-dorreen interkonexio-sistema baten arkitektura definitu da teknologia hori bera erabiliz.

Emaitzek arkitektura funtzional baten diseinu osoa eta sistemak funtzionatzeko behar diren baldintzak erakusten dute. Gainera, inplementazioari lotutako erronka nagusiak identifikatu dira (hau da, seinaleen isolamendua eta interferentziak ezeztatzea), eta horiek gaitzeko behar diren etapak definitu dira.

C3 ekarpenarekin lotutako argitalpenak honako hauek dira:

- L. Zhang et al., "ATSC 3.0 In-band Backhaul for SFN Using LDM with Full Backward Compatibility," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Hego Korea, 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971918.
- L. Zhang et al., "Using Layered Division Multiplexing for Wireless In-Band Distribution Links in Next Generation Broadcast Systems," IEEE Transactions on Broadcasting, vol. 67, no. 1, pp. 68-82, March 2021, doi: 10.1109/TBC.2020.2989638.
- W. Li et al., "Integrated Inter-Tower Wireless Communications Network for Terrestrial Broadcasting and Multicasting Systems," IEEE Transactions on Broadcasting aldizkarian argitaratzeko onartua.

1.4 Laburpena eta emaitzak

1.4.1 Broadcasterako NOMA eMBBn

eMBB 5Gren erabilera kasuetako bat da, non informazio eta entretenimendu zerbitzu tradizionalak multimedia aplikazio berritzaileekin konbinatzen diren. Izan ere, multimedia aplikazioen ezaugarriak eta erabiltzaileen beharrak erabat aldatu dira azken urteotan. Aldaketa horren adibide argiak 3D edo 360° bideo-edukia, 4k/8k zerbitzu-kalitatea, EA/EBn oinarritutako aplikazioak edo hodeiarekin interakzioa duten aplikazioak dira. Aplikazioen zerrendaz gain, eMBBk beste erronka teknologiko bati egin behar dio aurre: zerbitzuak edonorentzat eta edonon egon behar du bermatuta. Horren ondorioz, erabiltzaile-dentsitate handiko ekitaldiak eta tokiak kontuan hartu behar dira, hala nola estadioak, merkataritza-guneak, erakusketak, jaialdiak edo kontzertuak. Horregatik, sareak Gbps-eko kapazitateak eskaintzeko prest egon behar du.

Horregatik, sarearen espektroaren eraginkortasun orokorra hobetzeko, NOMA bezalako teknika eta teknologia berriak ikertu behar dira. Hala ere, hobekuntza nabarmena emateko, hainbat mailatako analisia egitea beharrezkoa da (hau da, PHY, MAC eta RRM). Alde batetik, PHY/MAC maila-azterketa egin behar da, proposatutako irtenbideen sendotasuna eta ahalmena ebaluatzeko. Bestalde, RRM modulua eraginkortasuna ebaluatu behar da, baliabideak esleitzeko fasea optimizatzeko. Ekarpene honetan analisi bi egiten dira.

PHY/MAC mailen analisiari dagokionez, lehenik eta behin, K1 artikuluan, NOMAn oinarritutako eta broadcast zerbitzua bermatzeko lehen 5G NR transtzeptorea diseinatuta dago. Lanak 5G NR arkitekturan oinarritutako PHY mailako arkitektura bat aurkezten du, kodetze

eta deskodetze prozesuek NOMA barne hartzeko aldaketa batzuk jasotzen dituen. Ebaluazioa multimedia-edukiaren banaketarekin lotuta diseinatutako erabilera-kasu batzuen gainean egiten da. Emaitzen arabera, ohiko TDMA eskemen ahalmen bera du. Aldi berean, zerbitzuen sendotasuna 4 dB ingurukoa da, eta horrek nabarmen hobetzen du zerbitzuaren erabilgarritasuna.

J1 artikuluan aurrerapen gehigarri bat aurkezten da sistemen diseinuan. Artikulu honek NOMAn oinarritutako 5G NR PHY/MAC arkitektura garatuagoa aurkezten du, HARQ birtransmisio-teknikak barne hartzen dituelarik. Gainera, arkitekturaren propagazio-kanal desafiatazaleen pean ebaluatuta dago (hau da, TDL). Definitutako arkitekturaren helburua broadcast eta unicast zerbitzuen arteko konbergentzia bermatzeko beharra asetzea da. Aztertutako erabilera-kasua broadcast eta unicast zerbitzuak batera dituen zelula-sare batean oinarritzen da, eta gNBk eduki bien banaketa bermatu behar du. Ebaluazioa egiteko hiru KPI erabiltzen dira: fidagarritasuna, latentsia eta throughput. Oro har, emaitzek NOMAk TDMA fidagarritasunean eta throughput-ean gaintzen duela erakusten dute. Gainera, kasu bietan (hau da, NOMA eta TDMA) latentsia balioak antzekoak eta onargarriak dira (hau da, 4 ms-tik beherakoak). Gainera, NOMAren LLak latentsia-osagai gehigarri bat du, SIC moduluaren ondorioz, eta hori latentsia-kalkuluetan kontuan hartzen da.

RRM mailaren analisiari dagokionez, K2 artikulua broadcast/unicast konbergentziako inguruneetan baliabideak esleitzeko gaitasunak aztertzen ditu, TDMA eta NOMA erabiliz. Hau baliabideen esleipena kudeatzeko bi RRM algoritmo berrirekin lortzen da (bata NOMAn oinarritua eta bestea TDMA). Emaitzetan oinarrituta, NOMA TDMA baino hobeto jarduten dela agregatutako unicast throughput eta zerbitzutatutako unicast erabiltzaile-kopuruari dagokienez nabarmendu behar da. Gainera, RRM algoritmoen konplexutasuna ere ebaluatzen da. Kasu honetan, NOMA konplexuagotzat jotzen da iterazio gehiago eskatzen baititu. NOMA algoritmoaren konplexutasuna murrizteko asmoz, algoritmoa gauzatzeko maiztasunean oinarritutako ikuspegi berri bat proposatzen da. Konplexutasuna murrizteko tekniken bidez NOMA TDMA baino hobeto jarduten den mailak aurkeztea eta horren arabera zerbitzuak kudeatzea posiblea da.

Gero, beste bi ekarpen aurkezten dira, haririk gabeko etorkizuneko komunikazioetarako erabilera espezifiko eta garrantzitsuko bi kasu adierazten dituztenak. Lehenik, J2 artikuluan, multicast transmisioen aplikazio berezi bat aurkezten da: RRM teknikak azpitaldeetako algoritmoetan. Artikuluak baliabideen erabilera onena deskribatzen du, erabiltzaileak azpitaldeetan banatzen baititu eta kodetze- eta

modulazio-eskema independenteak eta moldagarriak aplikatzen baititu, CQI berrelikaduraren arabera. NOMA duten azpitaldeen tekniken konbinazioaren inplikazio nagusiak azaltzen dira, eta azpitaldeak sortzeko bi algoritmo diseinatzen dira, bat NOMAn oinarritua eta bestea TDMA. Eraitzen arabera, murrizketarik aplikatzen ez bada, NOMA eta TDMA konfigurazio bidegabeak dituzte, zerbitzatutako erabiltzaile-kopuruaren eta gutxieneko edukieraren ikuspuntutik, hurrenez hurren. Gero, murrizketak aplikatu ondoren, NOMA hautagai hobetzat hartu behar da, TDMA baino ahalmen-erabiltzaileak hobeak eskaintzen baititu. Hala ere, analisi teoriko batean oinarrituta, NOMA eta TDMA tekniken inplementazio bateratuak algoritmo eraginkorragoak eman ditzakeela aurreikusten da.

Azkenik, aurreko ekarpenaren azken ondorioa erreferentziatuz hartuta, J3 artikuluan RRM eskema aurreratuetarako NOMA eta TDMA konbinazioa sakon aztertzen da. Azterlan hau etorkizuneko zerbitzuak inplementatzeko garrantzitsua izatea espero den beste erabilera-kasu batean definitzen da: komunikazioak mmWave bandetan. Proposatutako RRM ereduak probatzeko, dentsitate handiko inguruneetan multimedia-edukiaren eskariaren araberrako banaketan oinarritutako erabilera-kasu bat erabili da. Ereduen ebaluazioa throughput-ari, kapazitateari eta erabilgarritasunari dagokienez egiten da. Erabiltzek erakusten dutenez, RRM konbinatuen teknikak teknika bakarreko RRM algoritmoen errendimendua %50 inguru hobetzen dute, eta aurreikutzitako artean errendimendu hobea duen RRM ereduak adierazten da.

1.4.2 Aplikazio kritikoetarako NOMA URLLCn

URLLCK eMBB aplikazioetatik oso bestelako ezaugarriak dituzten aplikazio ugari biltzen ditu. Izan ere, URLLC fidagarritasun- eta latentzia-betekizun zorrotzak dituelako nabarmentzen da, 1.1 atalean zehazten den bezala. Hari gabeko 4.0 Industriako loturak [197] URLLCren kasurik adierazgarrienetako bat dira, non transmisioa industria-inguruneen hedapen-baldintza gogorretan gertatzen den. 4.0 Industriari buruzko aplikazioak produkzio-kate automatizatuekin lotuta daude, non makinak prozesuaren funtsezko elementuak diren. Adibidez, muntaketa, enbalajea, paletizazioa eta fabrikazioa.

5Gk ordezkatzen duen aplikazioen eta teknologien ekosistema URLLC aplikazioen haririk gabeko komunikazioen liderra izateko hautagai sendoa bada ere, une honetan industria-sistema gehien oinarrian dagoen teknologia IEEE 802.11 da, hau da Wi-Fi. Hasieran, haririk gabeko estandarren 802.11 familia industria-komunikazioetarako diseinatu ez bazen ere, industria-aplikazioetarako hautagai gisa ere aurreikutzitako dira, eskura dituzten gailu-sorta handiagatik, sare-inplementazioengatik eta

komunikazio-eremu ia guztietan dituzten aplikazioengatik. Hala ere, 802.11 estandarren fidagarritasuna mugatua da oraindik, eta ez dute determinismorik bermatzen. Bi eragozpen horiek industrian Wi-Fia masiboki ezartzea eragotzi dute. Horregatik, industria-komunikazioek 802.11 estandarren industria-betekizunen eta fidagarritasunaren arteko aldea ezabatuko duten konponbideak behar dituzte.

Industria-komunikazioei sendotasun handiagoa emateko, NOMA bezalako teknika eta teknologia berriak hartu behar dira kontuan. Aurreko ekarpenean deskribatutako ikuspegiari jarraituz, proposamenak eta horien ebaluazioak adierazgarriak direla bermatzeko bi mailatako azterketa behar da. Lehenik eta behin, gutxieneko fidagarritasun-maila onargarria bermatuko duten PHY geruzak diseinatu eta probatu behar dira, eta MAC geruzekin konbinatu, loturaren kalitate orokorra hobetzeko, birtramisioak bezalako mekanismoekin. Bigarrenik, RRM mailan lor daitekeen efizientzia espektrala hobetu daitekeen aztertzea beharrezkoa da. Ekarpenean aurkeztutako bost artikulutan bilduta.

PHY/MAC mailako analisiari dagokionez, K3 artikuluan NOMA eta 802.11 estandarra konbinatzean lortutako jardunaren aurretiazko ebaluazioa aurkezten du. Analiak hari gabeko komunikazio-sare industrial bat erabiltzen du, konfigurazio-parametro aldakorrekin. Emaitzek NOMAk zerbitzu kritikoetan emaitza hobek ematen dituela, eta hobekuntza hori areagotu egiten dela zerbitzu kritikoetan eta ez-kritikoetan arteko desoreka handitu ahala adierazten dute.

J4 artikulua PHY mailako transtzeptore-arkitektura oso bat proposatzen du, ingurunerako sarbidea eta denbora-domeinuko birtransmisioak kudeatzen dituen super-trama eskema batekin konbinatuta. Aurkeztutako komunikazio-sistemaren helburua bi zerbitzu-multzo desberdin eskaintzea da. Lehenengo zerbitzu-motak zerbitzu kritikoak (Critical Service, CS) barne hartzen ditu, bai fidagarritasunean bai latentzian murrizketa zorrotzak dituztenak. Komunikazio-sistema berak bigarren zerbitzu-talde bat ere transmititu beharko luke, esfortzurik onena (Best Effort, BE) izenekoa, betekizun lasaiagoekin. Oro har, NOMAk TDMA baino errendimendu-maila hobek erakusten ditu, batez ere CSrako. Latentziari dagokionez, NOMAk eta TDMAk antzeko emaitzak dituzte. Hala ere, batez besteko latentziaren desbiderapena txikiagoa da NOMAn, eta horrek esan nahi du komunikazioak deterministagoak direla kasu honetan.

Ondoren, K4 artikulua dibertsitate espazialean oinarritutako birtransmisio eskemek duten eragina ebaluatzen du. Bereziki, transmisore ugaridun sare konfigurazioak probatzen dira, non hasierako transmisioa eta birtransmisioak kokapen fisiko desberdinak dituzten sarbide-gune

(Access Point, AP) ezberdinek egiten dituzten. Emaizten arabera, nahiz eta errendimendua asko handitu transmisore askorekin, fidagarritasunaren eta eskainitako ahalmenaren arteko konpromisoa onartu behar da. Konpromisoa beharrezkoa da, birtransmisio gehiegik eskainitako gaitasuna murriztuko bailukete.

J5 artikuluan, denbora-banaketan eta transmisore ugaritan oinarritutako birtransmisio eskemak 4.3 ekarpenean aurkeztutako NOMAn oinarritutako 802.11 transtzeptorearekin konbinatzen dira. Kasu honetan, super-trama egitura ezberdinak proposatzen dira, non bi birtransmisio eskemak (denboran eta transmisore ugaritan oinarritutakoak) hurrengo konfigurazio aukeran arabera aurkezten diren: MCS, birtransmisio kopurua eta IL. Emaiztak eskalagarritasunaren, fidagarritasunaren eta latentziaren arabera aztertzen dira. Arkitektura honek fidagarritasuna nabarmen hobetzen du bi geruzetarako. Gainera, latentzia balio baxuak (UL ez da 250 μ s-tik gorakoa) eta jitter balio onargarriak (bereziki 10 dBtik aurrera) lortzen dira.

Bestalde, RRM mailaren analisiari dagokionez, tesi honen ekarpen nagusia J6 artikulua da. Lan honek 5G URLLCren ingurune industrialetarako NOMA eta TDMA oinarritutako RRM modulu espezifikoak garatzea proposatzen du. RRM moduluak probatzeko erabilera-kasu industrial tipikoko bat definitzen da. Azterlanak hainbat parametroren konfigurazioak aztertzen ditu. Aukera biak hainbat ikuspegitatik (ahalmena, kapazitatea eta latentzia) sakon aztertzen dira, eta optimizatu egiten dira hainbat baldintza betetzeko (gehieneko ahalmena/throughput-a eta gutxieneko denbora-zikloa). Oro har, emaitzek NOMA teknikak optimizazio-helburua sarearen ahalmena edo zerbitzatutako unicast erabiltzaile kopurua maximizatzea denean aukerarik egokiena direla iradokitzen dute.

Azkenik, ekarpen hau egitean ikasitako guztia erreferentziazat hartuta, J7 artikulua dibulgazio zientifikoko artikulua bat erakusten du. Ekarpen horrek 4.0 Industriaren barruko komunikazioen egungo egoeraren laburpena eta etorkizuneko industria-komunikazioak nolakoak izango diren aurreikusten du. Aipatzekoa da ekarpen hori Euskal Herriko dibulgazio-aldizkari batean argitaratu dela (Elhuyar Aldizkaria), eta, beraz, tokiko hizkuntza erabili da hura idazteko: euskara.

1.4.3 Full-duplex NOMA 6G saretarako

Hainbat haririk gabeko komunikazio-sistemen estandarizazio erakundek zerbitzuaren kalitatea hobetzeko etengabeko ahalegina egin duten arren, egia da erabiltzaileek eskatutako aplikazioak eta sistemak egungo teknologiak jasan dezakeena baino zorrotzagoak direla. Adibide argia

5G da. Izan ere, komunikazioen fidagarritasuna nabarmen hobetu bada ere, eta hainbat agertokitara egokitu daitekeen PHY konfiguragarria eskaintzen bada ere, badira 5Gren errendimendua gainditzen duten baldintzak dituzten aplikazioak. Hori dela eta, ikertzaileon komunitateak etorkizuneko komunikazio-estandarrek (hau da, 6G) gizartearen eskaeretara egokitzeko teknologia osagarriak diseinatzera bideratu behar du bere lana. Adibidez, 6Gn, esfortzuak zero latentziako edo espektro-eraginkortasun handiko sistemetan zentratu behar dira.

Bereziki, etorkizuneko komunikazio-estandarren efizientzia espektrala nabarmen handituko lukeen irtenbide bat NOMA teknikak full-duplex sistemak lortzeko erabiltzea da. Erronka horrek, lehenik eta behin, full-duplex NOMA sistema baten onura jasoko luketen erabilera praktikoko kasuak definitzea eskatzen du. Gainera, sistema probatzeko erabiliko den oinarritzko teknologia/estandarra erabaki behar da. Horrez gain, ikerketak NOMAn oinarritutako banda-seinaleak behar bezala sortu eta deskodetzeko gai den transmisorearen eta hartzailearen arkitekturaren definizioa behar du. Funtsezko beste zeregin bat full-duplex NOMA arkitektura baten sistemaren diseinuarekin erlazionatuta dauden arazo eta erronkak identifikatzea da. Ondoren, teknologiaren egungo egoera kontuan hartuta, egon daitezkeen irtenbideak adierazi behar dira. Zehazki, ekarpen honek ikerketa-erronka horietako batzuk lantzen ditu.

Lehenik, teknologiari eta erabilera-kasuei buruzko gaiak K5 artikuluan lantzen dira. Ekarpina honetan banda barruko backhaul-aren ikuspegia proposatzen da, non backhaul seinaleak hartzaile mugikorretarako zerbitzu sendo eta hartzaile finkoentzako datu-abiadura handiko zerbitzuekin batera frekuentzia-banda beraren barruan transmititzen den. Soluzio berri honek LDM erabiltzen du (NOMA kasu berezia) eta aurreko bertsioekin guztiz bateragarria den ATSC 3.0 uhin forma erabiliz transmititzen da. Soluzioaren eragozpen nagusia transmisoreak sortzen duen autointerferentzia-seinalea da. Horregatik, ezeztapen digitala erabiltzen duen modulu bat sartzen da, hiri-kanal tipiko (Typical Urban, TU) labur batean 30 eta 60 dB arteko berrelikadura begiztaren ezeztapena bermatzeko. Ezeztapenaren errendimendua lortu nahi den seinalearen eta autointerferentziaren arteko potentzia-diferentziaren arabera da.

Ondoren, J8 artikuluan, aurreko lanaren luzapen bat aurkezten da, non banda barruko hari gabeko banaketarako lotura-teknologia (Wireless In-band Distribution Link, WIDL) xehetasunez definitzen den. Lehenik eta behin, errendimendu-analisi baten bidez, ahalmen irabazia hurrengo belaunaldiko LTD zerbitzuak erabiliz aztertzen da, zeinak LDM multiplexazio-teknologia gisa erabiltzearen onurak nabarmentzen baititu. Ondoren, hartzailearen bloke-diagrama definitzen da eta kanal mugikorretarako ezeztapen-moduluaren errendimendua aztertzen da.

Emaitzek autointerferentzia LOS kasuan NLOS kasuan baino 10 dB gehiago ezeztatu daitezkeela erakusten dute. Azkenik, transmisore errealean lor daitezkeen seinale-isolamendua zehazten duen Ottawan (Kanada) egindako neurketa kanpaina baten emaitzak erakusten dira.

Azkenik, J9 artikuluan, WIDL sistemaren bilakaera proposatzen duen hirugarren ekarpen bat aurkeztu da. Kasu honetan, bi norabidekoa dorreen arteko komunikazio-sare bat (ITCN) deskribatzen da. Helburu nagusia SFN transmisoreen artean full-duplex transmisioa bermatzea da, datu-zerbitzu aberastuak eskaintzeko, hala nola IoT, larrialdi-ohartarazpena, autoen arteko konexioa edota beste datu-zerbitzu lokalizatu batzuk. Sarearen arkitektura eta malgutasunaren ondorioz egin daitezkeen aldaketak aurkezten dira. Ondoren, ITCN sareko nodo baten sistema osoaren bloke-diagrama definitzen da. Nabarmentzekoa da autointerferentzia-seinalearen ezeztapena hobetzeko modulu berriak sartu direla harrera-katean. Zehazki, ezeztatze katea bi teknika ezberdinen konbinazioan oinarritzen da. Lehenengoa antena moldagarriko teknikak dira, antenaren lobulu nagusiaren irabazia maximiza dezaketenak urruneko ITCN seinalearen norabidean. Bigarrena, tarte dinamikoaren mugak gainditzeko, ezeztapen modulua bi etapa konbinatzean datza: analogikoa eta digitala.

1.5 Bibliografia

- [1] *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021.*
- [2] Patrik Cerwall et al. "Ericsson mobility report". In: *On the Pulse of the Networked Society*. Hg. v. Ericsson (2015).
- [3] Zoran S Bojkovic, Dragorad A Milovanovic, and Tulsi Pawan Fowdur. *5G Multimedia Communication: Technology, Multiservices, and Deployment*. CRC Press, 2020.
- [4] ITU-R, Report ITU-R M.2370-0, "IMT traffic estimates for the years 2020 to 2030," Jul. 2015.
- [5] Mohammed S Elbamy et al. "Toward low-latency and ultra-reliable virtual reality". In: *IEEE Network* 32.2 (2018), pp. 78–84.
- [6] *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022.*
- [7] ITU-R Rec. ITU-R M. 2083-0, "IMT Vision — Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Sept. 2015.

- [8] ITU-R Rec. ITU-R M. 2410-0, "Minimum requirements related to technical performance for IMT-2020 radio interface(s)," Nov. 2017.
- [9] Mansoor Shafi et al. "5G: A tutorial overview of standards, trials, challenges, deployment, and practice". In: *IEEE journal on selected areas in communications* 35.6 (2017), pp. 1201–1221.
- [10] TS 38.201, *Tech. Spec. Group Services and System Aspects, "NR; Physical layer; General description," V15.0.0, January 2018.*
- [11] TR 21.916, *Tech. Spec. Group Services and System Aspects, "Release 16 Description; Summary of Rel-16 Work Items (Release 16)," V1.0.0, December 2018.*
- [12] Amitabha Gosh et al. "5G Evolution: View on 5G Cellular Technology Beyond 3GPP Release 15". In: *IEEE Access* 7 (2019), pp. 127639–127651.
- [13] Raúl Chávez-Santiago et al. "5G: The convergence of wireless communications". In: *Wireless Personal Communications* 83.3 (2015), pp. 1617–1642.
- [14] Luca Boero et al. "Satellite networking integration in the 5G ecosystem: Research trends and open challenges". In: *Ieee Network* 32.5 (2018), pp. 9–15.
- [15] Jon Montalban, Gabriel-Miro Muntean, and Pablo Angueira. "A utility-based framework for performance and energy-aware convergence in 5G heterogeneous network environments". In: *IEEE Transactions on Broadcasting* 66.2 (2020), pp. 589–599.
- [16] Massimo Condoluci et al. "Fixed-mobile convergence in the 5G Era: from hybrid access to converged core". In: *IEEE Network* 33.2 (2019), pp. 138–145.
- [17] Shanzhi Chen et al. "Vision, requirements, and technology trend of 6G: how to tackle the challenges of system coverage, capacity, user data-rate and movement speed". In: *IEEE Wireless Communications* 27.2 (2020), pp. 218–228.
- [18] Wei Feng et al. "When mmWave communications meet network densification: A scalable interference coordination perspective". In: *IEEE Journal on Selected Areas in Communications* 35.7 (2017), pp. 1459–1471.
- [19] Long Zhang et al. "A survey on 5G millimeter wave communications for UAV-assisted wireless networks". In: *IEEE Access* 7 (2019), pp. 117460–117504.

- [20] Behrooz Makki et al. "A survey of NOMA: Current status and open research challenges". In: *IEEE Open Journal of the Communications Society* 1 (2020), pp. 179–189.
- [21] SM Riazul Islam et al. "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges". In: *IEEE Communications Surveys & Tutorials* 19.2 (2016), pp. 721–742.
- [22] Nabil Svenh Loghin et al. "Non-uniform constellations for ATSC 3.0". In: *IEEE Transactions on Broadcasting* 62.1 (2016), pp. 197–203.
- [23] Evgeny Khorov et al. "A tutorial on IEEE 802.11 ax high efficiency WLANs". In: *IEEE Communications Surveys & Tutorials* 21.1 (2018), pp. 197–216.
- [24] Hsin-Hung Cho et al. "Integration of SDR and SDN for 5G". In: *IEEE Access* 2 (2014), pp. 1196–1204.
- [25] Alcardo Alex Barakabitze et al. "5G network slicing using SDN and NFV: A survey of taxonomy, architectures and future challenges". In: *Computer Networks* 167 (2020), p. 106984.
- [26] Sulastri Manap et al. "Survey of radio resource management in 5g heterogeneous networks". In: *IEEE Access* 8 (2020), pp. 131202–131223.
- [27] Nadezhda Chukhno et al. "Efficient Management of Multicast Traffic in Directional mmWave Networks". In: *IEEE Transactions on Broadcasting* (2021).
- [28] Yi Fang et al. "Design guidelines of low-density parity-check codes for magnetic recording systems". In: *IEEE Communications Surveys & Tutorials* 20.2 (2018), pp. 1574–1606.
- [29] Hong Chen, Robert G Maunder, and Lajos Hanzo. "A survey and tutorial on low-complexity turbo coding techniques and a holistic hybrid ARQ design example". In: *IEEE Communications Surveys & Tutorials* 15.4 (2013), pp. 1546–1566.
- [30] Zunaira Babar et al. "Polar codes and their quantum-domain counterparts". In: *IEEE Communications Surveys & Tutorials* 22.1 (2019), pp. 123–155.
- [31] Mahmoud A Albreem, Markku Juntti, and Shahriar Shahabuddin. "Massive MIMO detection techniques: A survey". In: *IEEE Communications Surveys & Tutorials* 21.4 (2019), pp. 3109–3132.
- [32] Emil Björnson and Luca Sanguinetti. "Scalable cell-free massive MIMO systems". In: *IEEE Transactions on Communications* 68.7 (2020), pp. 4247–4261.

- [33] Min Jia et al. "Broadband hybrid satellite-terrestrial communication systems based on cognitive radio toward 5G". In: *IEEE Wireless Communications* 23.6 (2016), pp. 96–106.
- [34] Xuemin Hong et al. "Cognitive radio in 5G: a perspective on energy-spectral efficiency trade-off". In: *IEEE Communications Magazine* 52.7 (2014), pp. 46–53.
- [35] Emilio Calvanese Strinati et al. "6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication". In: *IEEE Vehicular Technology Magazine* 14.3 (2019), pp. 42–50.
- [36] Syed Junaid Nawaz et al. "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future". In: *IEEE Access* 7 (2019), pp. 46317–46350.
- [37] Lin Zhang, Ying-Chang Liang, and Dusit Niyato. "6G Visions: Mobile ultra-broadband, super internet-of-things, and artificial intelligence". In: *China Communications* 16.8 (2019), pp. 1–14.
- [38] Walid Saad, Mehdi Bennis, and Mingzhe Chen. "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems". In: *IEEE network* 34.3 (2019), pp. 134–142.
- [39] Harish Viswanathan and Preben E Mogensen. "Communications in the 6G era". In: *IEEE Access* 8 (2020), pp. 57063–57074.
- [40] Kazi Mohammed Saidul Huq et al. "THz communications for mobile heterogeneous networks". In: *IEEE Communications Magazine* 56.6 (2018), pp. 94–95.
- [41] Nan Chi et al. "Visible Light Communication in 6G: Advances, Challenges, and Prospects". In: *IEEE Vehicular Technology Magazine* 15.4 (2020), pp. 93–102.
- [42] Bomin Mao, Yuichi Kawamoto, and Nei Kato. "AI-based joint optimization of QoS and security for 6G energy harvesting internet of things". In: *IEEE Internet of Things Journal* 7.8 (2020), pp. 7032–7042.
- [43] Sanjay Goyal et al. "Full duplex cellular systems: will doubling interference prevent doubling capacity?" In: *IEEE Communications Magazine* 53.5 (2015), pp. 121–127.
- [44] Carlos De Lima et al. "Convergent communication, sensing and localization in 6G systems: An overview of technologies, opportunities and challenges". In: *IEEE Access* (2021).

- [45] Emilio Calvanese Strinati et al. "6G in the sky: On-demand intelligence at the edge of 3D networks". In: *ETRI Journal* 42.5 (2020), pp. 643–657.
- [46] Sooeun Song et al. "Analysis of wireless backhaul networks based on aerial platform technology for 6g systems". In: *Computers, Materials and Continua* 62.2 (2020), pp. 473–494.
- [47] Khaled B Letaief et al. "The roadmap to 6G: AI empowered wireless networks". In: *IEEE Communications Magazine* 57.8 (2019), pp. 84–90.
- [48] A. W. Scott and R. Frobenius. "Multiple Access Techniques: FDMA, TDMA, AND CDMA". In: *RF Measurements for Cellular Phones and Wireless Data Systems*. 2008, pp. 413–429.
- [49] B Sundar Rajan and Moon Ho Lee. "Quasi-cyclic dyadic codes in the Walsh-Hadamard transform domain". In: *IEEE Transactions on Information Theory* 48.8 (2002), pp. 2406–2412.
- [50] Hongxiang Li et al. "OFDMA capacity analysis in MIMO channels". In: *IEEE transactions on information theory* 56.9 (2010), pp. 4438–4446.
- [51] Linglong Dai et al. "A survey of non-orthogonal multiple access for 5G". In: *IEEE communications surveys & tutorials* 20.3 (2018), pp. 2294–2323.
- [52] Kenichi Higuchi and Anass Benjebbour. "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access". In: *IEICE Transactions on Communications* 98.3 (2015), pp. 403–414.
- [53] Lei Wang et al. "Sparse code multiple access-towards massive connectivity and low latency 5G communications". In: *Telecommun. Netw. Technol* 5.5 (2015).
- [54] Alireza Bayesteh et al. "Blind detection of SCMA for uplink grant-free multiple-access". In: *2014 11th international symposium on wireless communications systems (ISWCS)*. IEEE. 2014, pp. 853–857.
- [55] Mojtaba Vaezi et al. "Interplay between NOMA and other emerging technologies: A survey". In: *IEEE Transactions on Cognitive Communications and Networking* 5.4 (2019), pp. 900–919.
- [56] Omar Maraqa et al. "A survey of rate-optimal power domain NOMA with enabling technologies of future wireless networks". In: *IEEE Communications Surveys & Tutorials* 22.4 (2020), pp. 2192–2235.
- [57] Zhiguo Ding et al. "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends". In: *IEEE Journal on Selected Areas in Communications* 35.10 (2017), pp. 2181–2195.

- [58] Reza Hoshyar, Ferry P Wathan, and Rahim Tafazolli. "Novel low-density signature for synchronous CDMA systems over AWGN channel". In: *IEEE Transactions on Signal Processing* 56.4 (2008), pp. 1616–1626.
- [59] Dongning Guo and Chih-Chun Wang. "Multiuser detection of sparsely spread CDMA". In: *IEEE journal on selected areas in communications* 26.3 (2008), pp. 421–431.
- [60] Reza Hoshyar, Razieh Razavi, and Mohammad Al-Imari. "LDS-OFDM an efficient multiple access technique". In: *2010 IEEE 71st Vehicular Technology Conference*. IEEE. 2010, pp. 1–5.
- [61] Mohammed Al-Imari and Reza Hoshyar. "Reducing the peak to average power ratio of LDS-OFDM signals". In: *2010 7th International Symposium on Wireless Communication Systems*. IEEE. 2010, pp. 922–926.
- [62] Mohammed Al-Imari et al. "Subcarrier and power allocation for LDS-OFDM system". In: *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*. IEEE. 2011, pp. 1–5.
- [63] Hosein Nikopour and Hadi Baligh. "Sparse code multiple access". In: *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE. 2013, pp. 332–336.
- [64] Mahmoud Taherzadeh et al. "SCMA codebook design". In: *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*. IEEE. 2014, pp. 1–5.
- [65] Hosein Nikopour et al. "SCMA for downlink multiple access of 5G wireless networks". In: *2014 IEEE global communications conference*. IEEE. 2014, pp. 3940–3945.
- [66] Kelvin Au et al. "Uplink contention based SCMA for 5G radio access". In: *2014 IEEE Globecom workshops (GC wkshps)*. IEEE. 2014, pp. 900–905.
- [67] Thomas Cover. "Broadcast channels". In: *IEEE Transactions on Information Theory* 18.1 (1972), pp. 2–14.
- [68] P Bergmans and Thomas Cover. "Cooperative broadcasting". In: *IEEE Transactions on Information Theory* 20.3 (1974), pp. 317–324.
- [69] Linglong Dai et al. "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends". In: *IEEE Communications Magazine* 53.9 (2015), pp. 74–81.

- [70] Xiaoming Dai et al. "Pattern division multiple access: A new multiple access technology for 5G". In: *IEEE Wireless Communications* 25.2 (2018), pp. 54–60.
- [71] Jiachen Huang et al. "Scalable video broadcasting using bit division multiplexing". In: *IEEE Transactions on Broadcasting* 60.4 (2014), pp. 701–706.
- [72] Katsutoshi Kusume, Gerhard Bauch, and Wolfgang Utschick. "IDMA vs. CDMA: Analysis and comparison of two multiple access schemes". In: *IEEE Transactions on wireless communications* 11.1 (2011), pp. 78–87.
- [73] Yuanwei Liu et al. "Non-orthogonal multiple access for 5G and beyond". In: *Proceedings of the IEEE* 105.12 (2017), pp. 2347–2381.
- [74] David Tse and Pramod Viswanath. *Fundamentals of wireless communication*. Cambridge university press, 2005.
- [75] Eduardo Garro et al. "Information-Theoretic Analysis and Performance Evaluation of Optimal Demappers for Multi-Layer Broadcast Systems". In: *IEEE Transactions on Broadcasting* 64.4 (2018), pp. 781–790.
- [76] Jon Montalban et al. "Multimedia multicast services in 5G networks: Subgrouping and non-orthogonal multiple access techniques". In: *IEEE Communications Magazine* 56.3 (2018), pp. 91–95.
- [77] Anass Benjebbour et al. "Concept and practical considerations of non-orthogonal multiple access (NOMA) for future radio access". In: *2013 International Symposium on Intelligent Signal Processing and Communication Systems*. IEEE. 2013, pp. 770–774.
- [78] Aritz Abuin et al. "Complexity Reduction Techniques for NOMA-based RRM Algorithms in 5G Networks". In: *2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech)*. IEEE. 2020, pp. 86–89.
- [79] Huseyin Haci, Huiling Zhu, and Jiangzhou Wang. "Performance of non-orthogonal multiple access with a novel asynchronous interference cancellation technique". In: *IEEE Transactions on Communications* 65.3 (2017), pp. 1319–1335.
- [80] Jingmin Liu, Ying Li, and Yue Sun. "Detection of symbol-asynchronous uplink NOMA with imperfect time offsets". In: *IET Communications* 14.21 (2020), pp. 3873–3881.

- [81] Luke Fay et al. "An overview of the ATSC 3.0 physical layer specification". In: *IEEE Transactions on Broadcasting* 62.1 (2016), pp. 159–171.
- [82] Liang Zhang et al. "Layered-division-multiplexing: Theory and practice". In: *IEEE Transactions on Broadcasting* 62.1 (2016), pp. 216–232.
- [83] Jon Montalbán et al. "Cloud transmission: System performance and application scenarios". In: *IEEE Transactions on Broadcasting* 60.2 (2014), pp. 170–184.
- [84] Lachlan Michael and David Gómez-Barquero. "Bit-interleaved coded modulation (BICM) for ATSC 3.0". In: *IEEE Transactions on Broadcasting* 62.1 (2016), pp. 181–188.
- [85] Kyung-Joong Kim et al. "Low-density parity-check codes for ATSC 3.0". In: *IEEE transactions on broadcasting* 62.1 (2016), pp. 189–196.
- [86] Sung Ik Park et al. "Low complexity layered division multiplexing for ATSC 3.0". In: *IEEE Transactions on broadcasting* 62.1 (2015), pp. 233–243.
- [87] Sung Ik Park et al. "Low complexity layered division multiplexing system for the next generation terrestrial broadcasting". In: *2015 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*. IEEE. 2015, pp. 1–3.
- [88] David Gómez-Barquero and Osvaldo Simeone. "LDM versus FDM/TDM for unequal error protection in terrestrial broadcasting systems: An information-theoretic view". In: *IEEE Transactions on Broadcasting* 61.4 (2015), pp. 571–579.
- [89] Jon Montalban et al. "Performance study of layered division multiplexing based on SDR platform". In: *IEEE Transactions on Broadcasting* 61.3 (2015), pp. 436–444.
- [90] Cristina Regueiro et al. "LDM core services performance in ATSC 3.0". In: *IEEE Transactions on Broadcasting* 62.1 (2016), pp. 244–252.
- [91] Sung-Ik Park et al. "Field test results of layered division multiplexing for the next generation DTV system". In: *IEEE Transactions on Broadcasting* 63.1 (2016), pp. 260–266.
- [92] Sung-Ik Park et al. "Field comparison tests of LDM and TDM in ATSC 3.0". In: *IEEE Transactions on Broadcasting* 64.3 (2017), pp. 637–647.

- [93] Eneko Iradier et al. "Adaptive resource allocation in LTE vehicular services using LDM". In: *2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. IEEE. 2016, pp. 1–6.
- [94] Jae-young Lee et al. "ATSC 3.0 and LTE cooperation for LDM and SHVC based mobile broadcasting". In: *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. IEEE. 2019, pp. 1–2.
- [95] Liang Zhang et al. "Layered-division multiplexing: An enabling technology for multicast/broadcast service delivery in 5G". In: *IEEE Communications Magazine* 56.3 (2018), pp. 82–90.
- [96] Eduardo Garro et al. "LDM integration into 5G NR: Use cases and PHY performance analysis". In: *2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. IEEE. 2020, pp. 1–5.
- [97] Md Shantanu Islam et al. "Layer division multiplexing for 5G DL transmission within ultra-dense heterogeneous networks". In: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE. 2020, pp. 1–7.
- [98] Erik Stare, JJ Giménez, and P Klenner. "WIB: a new system concept for digital terrestrial television (DTT)". In: *IBC 2016 Conference*. IET. 2016.
- [99] 3GPP TR 36.866, "Study on network-assisted interference cancellation and suppression (NAICS) for LTE v.12.0.1," Mar. 2014.
- [100] Qiangze Chi, Xin Zhang, and Dacheng Yang. "Detection-assisted interference parameter estimation and interference cancellation for LTE-advanced system". In: *2016 IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC)*. IEEE. 2016, pp. 229–233.
- [101] 3GPP TR 36.859, "Study on Downlink Multiuser Superposition Transmission (MUST) for LTE v.13.0.0," Jan. 2016.
- [102] Jinho Choi. "On the power allocation for a practical multiuser superposition scheme in NOMA systems". In: *IEEE Communications Letters* 20.3 (2016), pp. 438–441.
- [103] Yifei Yuan, Zhifeng Yuan, and Li Tian. "5G non-orthogonal multiple access study in 3GPP". In: *IEEE Communications Magazine* 58.7 (2020), pp. 90–96.
- [104] 3GPP TR 38.812, "Study on Non-Orthogonal Multiple Access (NOMA) for NR v.16.0.0," Dec. 2018.

- [105] Mehmet Mert Şahin and Huseyin Arslan. "Waveform-domain noma: The future of multiple access". In: *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2020, pp. 1–6.
- [106] Hei Victor Cheng, Emil Björnson, and Erik G Larsson. "Performance analysis of NOMA in training-based multiuser MIMO systems". In: *IEEE Transactions on Wireless communications* 17.1 (2017), pp. 372–385.
- [107] Dhanushka Kudathanthirige and Gayan Amarasuriya Aruma Baduge. "NOMA-aided multicell downlink massive MIMO". In: *IEEE Journal of Selected Topics in Signal Processing* 13.3 (2019), pp. 612–627.
- [108] Xin Liu et al. "Highly efficient 3-D resource allocation techniques in 5G for NOMA-enabled massive MIMO and relaying systems". In: *IEEE Journal on Selected Areas in Communications* 35.12 (2017), pp. 2785–2797.
- [109] Xiaoming Chen, Rundong Jia, and Derrick Wing Kwan Ng. "The application of relay to massive non-orthogonal multiple access". In: *IEEE Transactions on Communications* 66.11 (2018), pp. 5168–5180.
- [110] Yikai Li and Gayan Amarasuriya Aruma Baduge. "NOMA-aided cell-free massive MIMO systems". In: *IEEE Wireless Communications Letters* 7.6 (2018), pp. 950–953.
- [111] Di Zhang et al. "Capacity analysis of NOMA with mmWave massive MIMO systems". In: *IEEE Journal on Selected Areas in Communications* 35.7 (2017), pp. 1606–1618.
- [112] Zhiguo Ding and H Vincent Poor. "Design of massive-MIMO-NOMA with limited feedback". In: *IEEE Signal Processing Letters* 23.5 (2016), pp. 629–633.
- [113] Theodore S Rappaport et al. *Millimeter wave wireless communications*. Pearson Education, 2015.
- [114] Zhiguo Ding et al. "NOMA meets finite resolution analog beamforming in massive MIMO and millimeter-wave networks". In: *IEEE Communications Letters* 21.8 (2017), pp. 1879–1882.
- [115] Mojtaba Ahmadi Almasi, Mojtaba Vaezi, and Hani Mehrpouyan. "Impact of beam misalignment on hybrid beamforming NOMA for mmWave communications". In: *IEEE transactions on communications* 67.6 (2019), pp. 4505–4518.

- [116] Caijun Zhong and Zhaoyang Zhang. "Non-orthogonal multiple access with cooperative full-duplex relaying". In: *IEEE Communications Letters* 20.12 (2016), pp. 2478–2481.
- [117] Xinwei Yue et al. "Exploiting full/half-duplex user relaying in NOMA systems". In: *IEEE Transactions on Communications* 66.2 (2017), pp. 560–575.
- [118] Jung-Bin Kim and In-Ho Lee. "Non-orthogonal multiple access in coordinated direct and relay transmission". In: *IEEE Communications Letters* 19.11 (2015), pp. 2037–2040.
- [119] Wonjae Shin et al. "Non-orthogonal multiple access in multi-cell networks: Theory, performance, and practical challenges". In: *IEEE Communications Magazine* 55.10 (2017), pp. 176–183.
- [120] Md Shipon Ali, Ekram Hossain, and Dong In Kim. "Coordinated multipoint transmission in downlink multi-cell NOMA systems: Models and spectral efficiency performance". In: *IEEE Wireless Communications* 25.2 (2018), pp. 24–31.
- [121] Wonjae Shin et al. "Coordinated beamforming for multi-cell MIMO-NOMA". In: *IEEE Communications Letters* 21.1 (2016), pp. 84–87.
- [122] Yuanwei Liu et al. "Nonorthogonal multiple access in large-scale underlay cognitive radio networks". In: *IEEE Transactions on Vehicular Technology* 65.12 (2016), pp. 10152–10157.
- [123] Lu Lv et al. "Design of cooperative non-orthogonal multicast cognitive multiple access for 5G systems: User scheduling and performance analysis". In: *IEEE Transactions on Communications* 65.6 (2017), pp. 2641–2656.
- [124] Lu Lv et al. "When NOMA meets multiuser cognitive radio: Opportunistic cooperation and user scheduling". In: *IEEE Transactions on Vehicular Technology* 67.7 (2018), pp. 6679–6684.
- [125] Zhiguo Ding, Pingzhi Fan, and H Vincent Poor. "Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions". In: *IEEE Transactions on Vehicular Technology* 65.8 (2015), pp. 6010–6023.
- [126] Yuanwei Liu et al. "Enhancing the physical layer security of non-orthogonal multiple access in large-scale networks". In: *IEEE Transactions on Wireless Communications* 16.3 (2017), pp. 1656–1672.
- [127] Jianchao Chen, Liang Yang, and Mohamed-Slim Alouini. "Physical layer security for cooperative NOMA systems". In: *IEEE Transactions on Vehicular Technology* 67.5 (2018), pp. 4645–4649.

- [128] Beixiong Zheng et al. "Secure NOMA based two-way relay networks using artificial noise and full duplex". In: *IEEE Journal on Selected Areas in Communications* 36.7 (2018), pp. 1426–1440.
- [129] Chaoying Yuan et al. "Analysis on secrecy capacity of cooperative non-orthogonal multiple access with proactive jamming". In: *IEEE Transactions on Vehicular Technology* 68.3 (2019), pp. 2682–2696.
- [130] Hongjiang Lei et al. "On secure NOMA systems with transmit antenna selection schemes". In: *IEEE Access* 5 (2017), pp. 17450–17464.
- [131] Refik Caglar Kizilirmak, Corbett Ray Rowell, and Murat Uysal. "Non-orthogonal multiple access (NOMA) for indoor visible light communications". In: *2015 4th international workshop on optical wireless communications (IWOW)*. IEEE. 2015, pp. 98–101.
- [132] Hanaa Marshoud et al. "Non-orthogonal multiple access for visible light communications". In: *IEEE photonics technology letters* 28.1 (2015), pp. 51–54.
- [133] Liang Yin et al. "Performance evaluation of non-orthogonal multiple access in visible light communication". In: *IEEE Transactions on Communications* 64.12 (2016), pp. 5162–5175.
- [134] Rangeet Mitra and Vimal Bhatia. "Precoded chebyshev-NLMS-based pre-distorter for nonlinear LED compensation in NOMA-VLC". In: *IEEE Transactions on Communications* 65.11 (2017), pp. 4845–4856.
- [135] Yavuz Yapici and Ismail Guvenc. "Non-orthogonal multiple access for mobile VLC networks with random receiver orientation". In: *2019 IEEE Global Communications Conference (GLOBECOM)*. IEEE. 2019, pp. 1–6.
- [136] Bangjiang Lin et al. "Experimental demonstration of bidirectional NOMA-OFDMA visible light communications". In: *Optics express* 25.4 (2017), pp. 4348–4355.
- [137] Mohammad Mozaffari et al. "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems". In: *IEEE communications surveys & tutorials* 21.3 (2019), pp. 2334–2360.
- [138] Amin Farajzadeh, Ozgur Ercetin, and Halim Yanikomeroglu. "UAV data collection over NOMA backscatter networks: UAV altitude and trajectory optimization". In: *ICC 2019-2019 IEEE International Conference on Communications (ICC)*. IEEE. 2019, pp. 1–7.

- [139] Qingqing Wu and Rui Zhang. "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming". In: *IEEE Transactions on Wireless Communications* 18.11 (2019), pp. 5394–5409.
- [140] Qingqing Wu and Rui Zhang. "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network". In: *IEEE Communications Magazine* 58.1 (2019), pp. 106–112.
- [141] Jiakuo Zuo et al. "Resource allocation in intelligent reflecting surface assisted NOMA systems". In: *IEEE Transactions on Communications* 68.11 (2020), pp. 7170–7183.
- [142] Abdulkadir Celik et al. "A software-defined opto-acoustic network architecture for Internet of underwater things". In: *IEEE Communications Magazine* 58.4 (2020), pp. 88–94.
- [143] Samuel Ryecroft et al. "A first implementation of underwater communications in raw water using the 433 MHz frequency combined with a bowtie antenna". In: *Sensors* 19.8 (2019), p. 1813.
- [144] Tafseer Akhtar, Christos Tselios, and Ilias Politis. "Radio resource management: approaches and implementations from 4G to 5G and beyond". In: *Wireless Networks* 27.1 (2021), pp. 693–734.
- [145] Bin Liu, Hui Tian, and Lingling Xu. "An efficient downlink packet scheduling algorithm for real time traffics in LTE systems". In: *2013 IEEE 10th Consumer Communications and Networking Conference (CCNC)*. IEEE. 2013, pp. 364–369.
- [146] Georgios I Tsiropoulos et al. "Radio resource allocation techniques for efficient spectrum access in cognitive radio networks". In: *IEEE Communications Surveys & Tutorials* 18.1 (2014), pp. 824–847.
- [147] Muhammad Anjum Qureshi and Cem Tekin. "Fast learning for dynamic resource allocation in AI-enabled radio networks". In: *IEEE Transactions on Cognitive Communications and Networking* 6.1 (2019), pp. 95–110.
- [148] Ayaz Ahmad et al. "A survey on radio resource allocation in cognitive radio sensor networks". In: *IEEE Communications Surveys & Tutorials* 17.2 (2015), pp. 888–917.
- [149] Che-Wei Yeh et al. "Centralized interference-aware resource allocation for device-to-device broadcast communications". In: *2014 IEEE International Conference on Internet of Things (iThings), and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom)*. IEEE. 2014, pp. 304–307.

- [150] Manli Qian et al. "A super base station based centralized network architecture for 5G mobile communication systems". In: *Digital communications and Networks* 1.2 (2015), pp. 152–159.
- [151] Urs Hunkeler et al. "A case for centrally controlled wireless sensor networks". In: *Computer Networks* 57.6 (2013), pp. 1425–1442.
- [152] Marco Belleschi, Gábor Fodor, and Andrea Abrardo. "Performance analysis of a distributed resource allocation scheme for D2D communications". In: *2011 IEEE Globecom Workshops (GC Wkshps)*. IEEE. 2011, pp. 358–362.
- [153] David A Schmidt et al. "Distributed resource allocation schemes". In: *IEEE Signal Processing Magazine* 26.5 (2009), pp. 53–63.
- [154] Wenchao Li and Jing Zhang. "Cluster-based resource allocation scheme with QoS guarantee in ultra-dense networks". In: *IET Communications* 12.7 (2018), pp. 861–867.
- [155] Rong Wei, Ying Wang, and Yuan Zhang. "A two-stage cluster-based resource management scheme in ultra-dense networks". In: *2014 IEEE/CIC International Conference on Communications in China (ICCC)*. IEEE. 2014, pp. 738–742.
- [156] Uwe Herzog et al. "Quality of service provision and capacity expansion through extended-DSA for 5G". In: *Transactions on Emerging Telecommunications Technologies* 27.9 (2016), pp. 1250–1261.
- [157] Bassem Khalfi et al. "Dynamic power pricing using distributed resource allocation for large-scale DSA systems". In: *2015 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2015, pp. 1090–1094.
- [158] Le Liang, Geoffrey Ye Li, and Wei Xu. "Resource allocation for D2D-enabled vehicular communications". In: *IEEE Transactions on Communications* 65.7 (2017), pp. 3186–3197.
- [159] Haitao Zheng and Lili Cao. "Device-centric spectrum management". In: *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005*. IEEE. 2005, pp. 56–65.
- [160] Md Sipon Miah et al. "A cluster-based cooperative spectrum sensing in cognitive radio network using eigenvalue detection technique with superposition approach". In: *International Journal of Distributed Sensor Networks* 11.7 (2015), p. 207935.
- [161] Jia Jasmine Meng et al. "Collaborative spectrum sensing from sparse observations in cognitive radio networks". In: *IEEE Journal on Selected Areas in Communications* 29.2 (2011), pp. 327–337.

- [162] Jian Sun et al. "Uplink resource allocation for relay-aided device-to-device communication". In: *IEEE Transactions on Intelligent Transportation Systems* 19.12 (2018), pp. 3883–3892.
- [163] Syed Tariq Shah et al. "SC-FDMA-based resource allocation and power control scheme for D2D communication using LTE-A uplink resource". In: *EURASIP Journal on Wireless Communications and Networking* 2015.1 (2015), pp. 1–15.
- [164] Zhaohui Yang et al. "Downlink resource allocation and power control for device-to-device communication underlying cellular networks". In: *IEEE Communications Letters* 20.7 (2016), pp. 1449–1452.
- [165] Shruti Gupta et al. "Resource allocation for D2D links in the FFR and SFR aided cellular downlink". In: *IEEE Transactions on Communications* 64.10 (2016), pp. 4434–4448.
- [166] Lingyang Song, Yonghui Li, and Zhu Han. "Resource allocation in full-duplex communications for future wireless networks". In: *IEEE Wireless Communications* 22.4 (2015), pp. 88–96.
- [167] Hyungsik Ju and Rui Zhang. "Optimal resource allocation in full-duplex wireless-powered communication network". In: *IEEE Transactions on Communications* 62.10 (2014), pp. 3528–3540.
- [168] Rui Yin et al. "Joint spectrum and power allocation for D2D communications underlying cellular networks". In: *IEEE Transactions on Vehicular Technology* 65.4 (2015), pp. 2182–2195.
- [169] Zhenyu Zhou et al. "Energy-efficient resource allocation for D2D communications underlying cloud-RAN-based LTE-A networks". In: *IEEE Internet of Things Journal* 3.3 (2015), pp. 428–438.
- [170] Xiguang Zhang et al. "Research on overlay D2D resource scheduling algorithms for V2V broadcast service". In: *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*. IEEE. 2016, pp. 1–5.
- [171] Yiyang Pei and Ying-Chang Liang. "Resource allocation for device-to-device communications overlaying two-way cellular networks". In: *IEEE Transactions on Wireless Communications* 12.7 (2013), pp. 3611–3621.
- [172] Ali Alnoman, Lilatul Ferdouse, and Alagan Anpalagan. "Fuzzy-based joint user association and resource allocation in HetNets". In: *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*. IEEE. 2017, pp. 1–5.

- [173] Yongjun Xu et al. "Distributed resource allocation for cognitive HetNets with cross-tier interference constraint". In: *2017 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2017, pp. 1–6.
- [174] Pengshuo Ji, Jie Jia, and Jian Chen. "Joint optimization on both routing and resource allocation for millimeter wave cellular networks". In: *IEEE Access* 7 (2019), pp. 93631–93642.
- [175] Giuseppe Araniti et al. "A solution to the multicast subgroup formation problem in LTE systems". In: *IEEE Wireless Communications Letters* 4.2 (2015), pp. 149–152.
- [176] Fang Ye, Jing Dai, and Yibing Li. "Hybrid-clustering game Algorithm for Resource Allocation in Macro-Femto HetNet." In: *TIIS* 12.4 (2018), pp. 1638–1654.
- [177] Chungang Yang et al. "DISCO: Interference-aware distributed cooperation with incentive mechanism for 5G heterogeneous ultra-dense networks". In: *IEEE Communications Magazine* 56.7 (2018), pp. 198–204.
- [178] Bei Xie et al. "Joint spectral efficiency and energy efficiency in FFR-based wireless heterogeneous networks". In: *IEEE Transactions on Vehicular technology* 67.9 (2017), pp. 8154–8168.
- [179] Mu Yan et al. "Smart multi-RAT access based on multiagent reinforcement learning". In: *IEEE Transactions on Vehicular Technology* 67.5 (2018), pp. 4539–4551.
- [180] Lin Li et al. "Traffic-aware resource allocation schemes for HetNet based on CDSA". In: *IET Communications* 11.6 (2017), pp. 942–950.
- [181] Niwei Wang, Zesong Fei, and Jingming Kuang. "QoE-aware resource allocation for mixed traffics in heterogeneous networks based on Kuhn-Munkres algorithm". In: *2016 IEEE International Conference on Communication Systems (ICCS)*. IEEE. 2016, pp. 1–6.
- [182] Xing Xu et al. "A resource scheduling scheme based on utility function in CoMP environment". In: *2017 9th International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE. 2017, pp. 1–6.
- [183] Mikhail Gerasimenko et al. "Adaptive resource management strategy in practical multi-radio heterogeneous networks". In: *IEEE Access* 5 (2016), pp. 219–235.

- [184] Abdulkadir Celik et al. "Joint interference management and resource allocation for device-to-device (D2D) communications underlying downlink/uplink decoupled (DUDe) heterogeneous networks". In: *2017 IEEE international conference on communications (ICC)*. IEEE. 2017, pp. 1–6.
- [185] Sajjad Ahmad Khan, Adnan Kavak, Kerem Küçük, et al. "A novel fractional frequency reuse scheme for interference management in LTE-A HetNets". In: *IEEE Access* 7 (2019), pp. 109662–109672.
- [186] Junwei Huang et al. "Two-stage resource allocation scheme for three-tier ultra-dense network". In: *China Communications* 14.10 (2017), pp. 118–129.
- [187] Jose A Ayala-Romero, Juan J Alcaraz, and Javier Vales-Alonso. "Energy saving and interference coordination in HetNets using dynamic programming and CEC". In: *IEEE Access* 6 (2018), pp. 71110–71121.
- [188] Syed Ahsan Raza Naqvi et al. "Energy-aware radio resource management in D2D-enabled multi-tier HetNets". In: *IEEE Access* 6 (2018), pp. 16610–16622.
- [189] Xiaoming Wang et al. "Resource allocation in OFDMA heterogeneous networks for maximizing weighted sum energy efficiency". In: *Science China Information Sciences* 60.6 (2017), p. 062304.
- [190] Shuang Zhang et al. "Energy and spectrum efficient power allocation with NOMA in downlink HetNets". In: *Physical Communication* 31 (2018), pp. 121–132.
- [191] Nian Xia, Hsiao-Hwa Chen, and Chu-Sing Yang. "Radio resource management in machine-to-machine communications—A survey". In: *IEEE Communications Surveys & Tutorials* 20.1 (2017), pp. 791–828.
- [192] Le Liang et al. "Deep-learning-based wireless resource allocation with application to vehicular networks". In: *Proceedings of the IEEE* 108.2 (2019), pp. 341–356.
- [193] Tianyu Yang et al. "Deep reinforcement learning based resource allocation in low latency edge computing networks". In: *2018 15th international symposium on wireless communication systems (ISWCS)*. IEEE. 2018, pp. 1–5.
- [194] Peng Yu et al. "Deep learning-based resource allocation for 5G broadband TV service". In: *IEEE Transactions on Broadcasting* 66.4 (2020), pp. 800–813.

-
- [195] Hao Ye, Geoffrey Ye Li, and Biing-Hwang Fred Juang. “Deep reinforcement learning based resource allocation for V2V communications”. In: *IEEE Transactions on Vehicular Technology* 68.4 (2019), pp. 3163–3173.
- [196] Philipp Schulz et al. “Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture”. In: *IEEE Communications Magazine* 55.2 (2017), pp. 70–78.
- [197] Heiner Lasi et al. “Industry 4.0”. In: *Business & information systems engineering* 6.4 (2014), pp. 239–242.

2. Kapitulu

Ondorioak eta etorkizuneko lanak

2.1 Ondorioak

Tesi honen arabera, efizientzia espektrala 5G ekosisteman integratutako komunikazio-sistemen eta etorkizuneko belaunaldiaren diseinuen hobekuntza-eremu adierazgarrienetako bat da. Halaber, tesiak aplikazio berriek eskatzen dituzten baldintza zorrotzak betetzeko espektroraginkortasunean beharrezko hobekuntza eman dezaketen teknologiak identifikatu ditu. NOMA teknikak RRM eskemekin konbinatzean oinarritu da lana. Horrela, efizientzia espektralaren hobekuntza bi mailatan aplika daiteke, malgutasun eta onura handiagoak emanez.

5G ekosistemaren barruan sartzen diren aplikazio eta erabilera-kasuen multzo zabala kontuan hartuta, proposatutako irtenbideen ezaugarriak aplikazioaren araberakoak izango dira neurri handi batean. Beraz, aplikazioen lau familia posibleak erreferentziatzat hartuta, doktorego tesi hau hiru erabilera-kasutan zentratu da: eMBB, URLLC eta 5Gtik haratagoko komunikazioak. Azpimarratzekoa da tesi honek landutako arlo guztietan artearen egoeraren azterketa bat, soluzioaren diseinua, sistemaren ebaluazioa eta emaitzen azterketa aurkezten duela.

Lehenik eta behin, lehenengo ekarpena ("Broadcasterako NOMA eMBBn") multimedia aplikazioekin lotutako inguruneetan NOMA eta RRM batera erabiltzean datza. Lehenengo urratsa geruza fisikoan NOMA erabiltzen duen 5Gn oinarritutako komunikazio-sistema bat garatzea izan da. Balidazio-prozesuaren ondoren, ebaluazioak OMAN oinarritutako eskemek baino sendotasun eta gaitasun handiagoa erakutsi du erabilera-kasu bererako. Ondoren, lan hau luzatu egin da MAC geruzaren birtransmisioak barne hartuz eta soluzioa hedapen-kanal desafiatzaileetan probatuz. Kasu honetan, ebaluazioa hiru KPItan oinarritu da (fidagarritasuna, latentzia eta throughput-a). NOMAk, fidagarritasunean eta throughput-ean irabaziak eskaintzen ditu, aldi

berean, latentzia arriskuan jarri gabe. Gainera, emandako soluzioa broadcast eta unicast-zerbitzuen arteko konbergentzia ahalbidetzeko erabili da. RRM eskemetan oinarritutako eta PHY/MAC sistemekin konbinatutako ikuspegi berritzaileak proposatu dira. Baliabideen kudeaketa broadcast zerbitzuak eta unicast zerbitzuak elkarrekin bizi behar duten lan-inguruneetan aztertu da. Baliabideen kudeaketan NOMA-rekin lortutako emaitzak OMA teknikekin lortutakoak baino hobekiak dira. Ondoren, erabilera espezifikogoko kasuetara bideratutako bi irtenbide garatu dira. Lehenengoa baliabideen kudeaketan erabiltzaileak azpitaldeetan bateratzeko teknikak erabiltzean oinarritzen da, multicast edukia transmititzeko. Murrizketen garrantzia nabarmendu da, bai NOMA bai OMA bat egiten baitute soluzio bidegabeetan. Hala ere, erabilera-kasuaren araberrako murrizketak zehaztu ondoren, NOMA hautagai hobea dela eskaintutako errendimendua eta zerbitzutatutako erabiltzaile-kopurua handitzeko erakutsi du. Era berean, baliabideak kudeatzeko eskema berean NOMA eta OMA tekniken erabilera konbinatuak soluzio optimoak eman ditzakeela aurreikusitako da. Horregatik, ekarpen honen azken analisia mmWave bandetako komunikazioetan aplikatzeko RRM teknikak konbinatzean zetzan. Lortutako emaitzak erreferentziatutako hartuta, eredu konbinatuek teknika bakarrekotako ereduak %50 inguru hobetzen dituzte.

Bigarren ekarpen-arloari buruzko ikerketak ("Aplikazio kritikoetarako NOMA URLLCn") industria-komunikazioekin lotutako aplikazioetarako NOMA eta RRM tekniken optimizazio konbinatuaren abantailak aztertu ditu. Kasu honetan ere, lanaren hasiera PHY/MAC geruzen analisia izan da. Zehazki, 802.11n estandararekin bateragarria den transtzeptore-prototipo bat garatu da, eta NOMA erabili ahal izateko beharrezkoak diren gutxienezko aldaketak egin dira. Sistema diseinatzeko lehenengo urratsa arkitektura diseinatzea eta ingurunerako sarbidea kudeatzen duen super-tramaren egitura definitzea izan da. Gainera, sistemaren sendotasuna handitzeko denboraren eremuan egindako birtransmisioetan oinarritutako sistema bat erabili da. Diseinua probatzeko, eskakizun desberdinak dituzten ekipo mota ugari dituzten industria-instalazioak erabili dira erreferentzia gisa. Kasu honetan, bi zerbitzu mota bereizi dira: CS eta BE. Horietan, lehenak fidagarritasun- eta latentzia-baldintza kritikoak ditu, eta bigarrenak malgutasun handiagoa du eskakizunetan. Emaitzek NOMA OMA baino irabazi handiagoa ematen duela fidagarritasunari dagokionez, eta latentzia antzeko balioetan mantentzen duela adierazten dute. Hala ere, super-tramaren egitura hobetzeko marjina antzeman da. Horregatik, proposatutako PHY/MAC ereduarekin bateragarriak diren birtransmisio-mekanismoak sakonago aztertu dira. Lehenik eta behin, geruza bakarrekotako komunikazioetan denbora- eta

espazio-dibertsitateko birtransmisioen konfigurazioak proposatu eta aztertu dira. Lanaren ondorio nagusia dibertsitate espazialeko teknikek fidagarritasuna nabarmen handitzen dutela da. Hala ere, sarearen ahalmenarekin konpromiso bat onartu behar da. Horren ostean, frogatutako birtransmisio-eskemak NOMAn oinarritutako 802.11n prototipoarekin konbinatu dira. Kasu honetan, eredu bakoitza integratzeko hasierako super-trama aldatu egin da. Aurkeztutako emaitzek bi geruzetako fidagarritasuna aldi berean nabarmen handitu daitekeela, latentzia balio onargarrietan mantenduz adierazten dute. Bestalde, RRM moduluak 5G industria-komunikazioetan duen eragina ere aztertu da. Kasu honetan, erabilera-kasu berean erabili da, non zerbitzu kritikoak eta ez-kritikoak elkarrekin bizi behar diren, eta bi RRM eskema diseinatu dira, bata OMA oinarrituta eta bestea NOMAn oinarrituta. Ereduen errendimendua aztertzeko, erabilera-kasuaren parametroen balio-tarteak definitu dira, bi tekniketara duten eragina ikusteko. Gainera, ikuspegi globala emateko, azterlanak hainbat aldagai hartu ditu kontuan (throughput-a, latentzia eta kapazitatea). Oro har, NOMAk OMAk baino hobeto funtzionatzen du, bereziki erabilera-kasuaren baldintzak oso zorrotzak direnean.

Azkenik, hirugarren ekarpenari jarraituz (“Full-duplex NOMA 6G sareetarako”), etorkizuneko komunikazio-estandarren eraginkortasun espektrala hobetzeko, NOMA teknikak eta full-duplex komunikazioak konbinatzea proposatu da. Irrati-difusioko ekosistema bat hartu da erreferentziatzat, eta banda barruko backhaul seinalearen ikuspegia proposatu da. Backhaul seinalea zerbitzu mugikor sendo eta datu-abiadura handiko zerbitzu finkoekin frekuentzia-banda beraren barruan inplementatu da. Soluzio hori, WIDL izenekoa, errendimendu teorikoaren analisi batean eta eskatutako bloke-diagramaren definizio batean oinarritzen da. WIDL ATSC 3.0 uhin forman oinarritzen da eta zerbitzuak multiplexatzeko LDM erabiltzen du. Gainera, sortutako autointerferentzia-seinalea proposamen honen erronka nagusizat identifikatu da. Eragozpen hori gainditzeko (hau da, berrelikadura seinalearen efektua murrizteko), lehen urrats gisa, ezeztapen digitala aplikatu da. WIDL ezartzeko bideragarritasun-azterketarekin batera, neurketa kanpaina bat egin da Ottawan, Kanadan. Berrelikadura seinaleak izango zuen inpaktua kuantifikatzeko nahian, neurketen helburua ingurune errealean izan daitezkeen seinale-isolamendua zehaztea da. Ondoren, ITCN WIDL sistemaren bi noranzkoko bilakaera gisa deskribatu da, SFN transmisioaren artean full-duplex transmisioa bermatzeko, IoT, larrialdi-ohartarazpena, autoen arteko konexioa eta beste datu-zerbitzu lokalizatu batzuk barne hartzen dituzten datu-zerbitzu aberastuak eskaintzeko. Kasu honetan, berrelikadura seinalearen inpaktua murrizteko, transtzeptorearen arkitektura sakontasunez definitu eta harrera-katea hobetu egin da. Zehazki,

ezeztapen etapa hiru multzotan banatu da: antena moldagarria, ezeztapen analogikoa eta ezeztapen digitala.

2.2 Etorkizuneko lanak

Doktorego tesi hau garatu bitartean etorkizuneko komunikazio-sistementzat interes orokorrekoak izan daitezkeen etorkizuneko hainbat ikerketa-ildo identifikatu dira. Jarraian, lerro hauek tesi honetan aurkeztutako ekarpenen jarraipen gisa aurkezten dira.

Lehenik eta behin, lehenengo ekarpenari dagokionez, hauek dira identifikatutako etorkizuneko lanak:

- *Energetikoki eraginkorra den NOMA*: sareko erabiltzaile gehienek multimedia edukia kontsumitzeko bateriekin funtzionatzen duten gailuak erabiltzen dutela kontuan hartuta, NOMAn oinarritutako banaketa sistemen eraginkortasun energetikoa aztertu behar da. RRM eskemak energia gutxiago kontsumitzeko diseinatu daitezke, bai transmisorean bai hartzailean.
- *Konplexutasun baxuko soluzioak*: zalantzarik gabe, SIC moduluaren kostu konputazionala NOMA sistemen eragozpen nagusia da. Beraz, edozein hartzailearentzat eskuragarri egon dadin, konplexutasun txikiko irtenbideak garatu behar dira.
- *Zelula anitzeko kudeaketa*: NOMA teknikekin lotutako ikerketa gehienak zelula bakarreko agertokietan oinarritzen dira eta transmisoreen arteko lankidetzak kontuan ez da hartzen. Horregatik, aldi berean sare ugari kontuan hartzen dituzten sareak planifikatzeko azterlanak egin behar dira. Horrela, errendimendu orokorra hobe dezaketen transmisio sinkronizatu anizkoitzeko RRM eskemak gara litezke.

Hona hemen bigarren ekarpenari dagokionez identifikatutako etorkizuneko lanak:

- *Kontsumo energetikoa*: URLLCren erabilera-kasu adierazgarrienetako bat sentsore industrialen sareak dira, non sarea osatzen duten gailuek iraupen luzeko bateriak izan behar dituzten. Beraz, NOMAn oinarritutako teknikek ikuspegi globalago batetik duten eragina frogatzeko, fidagarritasunaren eta latentziaren analiziaz gain, hartzailearen energia-kontsumoa ere neurtu behar da.
- *Sarearen sinkronizazioa*: lan gehienek transmisoreen eta hartzaileen arteko sinkronizazio perfektua asumitzen dute, baina baldintza hori

ezin da beti bermatu. Beraz, interesgarria izan liteke proposatutako irtenbideak sinkronizazio-baldintza ez-perfektuetan probatzea.

- *Eraginkortasun espektralaren aldeko birtransmisioak*: oro har, nahiz eta birtransmisio-eskemak fidagarritasuna handitzeko hautagai ona diren, datu-paketeen transmisio erredundantea dakarte, efizientzia espektral orokorra murriztuz. Ondorioz, espektro-eraginkortasuna baldintzatzen ez duten birtransmisio-eskemak diseinatzeak inpaktu handia izango luke.

Azkenik, jarraian, hirugarren ekarpenarekin lotutako etorkizuneko ildoak azaltzen dira:

- *Ezeztapen analogikoa*: ezeztapen digitaleko eskemek berrelikadura seinalearen inpaktua murrizteko errendimendu positiboa erakutsi duten arren, gailu profesionalen tarte dinamiko mugatuak benetako inplementazioa mugatzen du. Beraz, errendimendu orokorra hobetzeko, ezeztapen analogikoko hainbat teknika egungo ezeztapen digitalaren soluzioarekin batera probatu behar dira.
- *Ezeztapen digitala*: azken urteetan, berrelikadura seinaleak ezeztatzeko eremuan, seinale digitalen prozesamenduan etorkizun handiko hainbat aurrerapen proposatu dira. Beraz, errendimendua kanal-baldintza desberdinetan neurtzeko ezeztapen digitalaren aukera desberdinak froga litezke.
- *Beamforming moldagarria*: antena diagramaren moldaketak nahi den seinalearen norabidearen irabazia maximizatzeaz gain, zarataren irabazia eta interferentzia-seinalea minimizatzea ere posiblea dela esan nahi du. Kasu horretan, mereziko luke beamforming moldagarriak eratzeko eskemak inplementatzea, jasotako berrelikadura seinalearen potentzia murrizteko, edozein ezeztatze-teknika aplikatu aurretik.
- *AAin oinarritutako teknikak*: literaturan AA sisteman oinarritutako alternatibek nabarmen areagotu dezaketela egungo ezeztapen-algoritmoen eraginkortasuna frogatu da. Beraz, berrelikadura seinalea zarata-zoruaren azpitik mantentzeko AAin oinarritutako teknikak transtzeptorearen arkitekturarekin nola konbinatu daitezkeen aztertu behar da.

3. Kapituluak

Publikatutako edo onartutako artikuluak

3.1 1. ekarpenarekin erlazionatutako artikuluak

3.1.1 Konferentzia-artikulua (K1)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- E. Iradier, J. Montalban, D. Romero, Y. Wu, L. Zhang and W. Li, "NOMA based 5G NR for PTM Communications," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Korea (South), 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971856.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore-n indexatutako konferentzia
- Saila: Konputazio zientziak eta ingeniari-tza
- SJR faktorea: 0,300

NOMA based 5G NR for PTM Communications

E. Iradier, J. Montalban, D. Romero
 Department of Communications Engineering
 University of the Basque Country (UPV/EHU)
 Plaza Torres Quevedo 1, Bilbao (Spain)
 {eneko.iradier, jon.montalban}@ehu.eus
 dromero007@ikasle.ehu.eus

Y. Wu, L. Zhang, W. Li
 Communications Research Centre
 CRC
 Ottawa, Canada
 {yiyuan.wu, liang.zhang, wei.li}@canada.ca

Abstract— Recent advances in broadband communications have led to the first standardization phase of 5G (Rel' 15). Several works present this novel standard as the main solution in order to cover all the new requirements that have arisen in the multimedia delivery industry. However, the latest 5G release does not include the option of transmitting traditional broadcast services. That is why, in this paper, Non-Orthogonal Multiple Access (NOMA) is presented as a promising candidate in order to boost the implementation of the broadcast/multicast communications within the 5G NR standard. Therefore, a 5G New Radio (NR) fully compliant simulation tool has been developed and NOMA multiplexing schemes have been added, introducing as few modifications as possible. The simulation platform and proposed techniques have been tested within two different use cases. Results present a better overall reliability performance of the communications by using NOMA. In fact, both services performance is improved when compared to traditional TDMA schemes, with a maximum gain around 4 dB.

Keywords— 5G, Broadcast, LDPC, Multicast, NOMA, TDMA

I. INTRODUCTION

The standardization process of the fifth generation of mobile communications (5G), which is considered the key for the new data consumption habits, has already started. In fact, the some of the most innovative NR concepts have been included in Release 15 [1]. One of the main improvements in comparison with previous releases is the use of newly designed LDPC codes (Low-Density Parity-Check). These codes increase the overall spectral efficiency, and so, more challenging wireless scenarios are feasible.

Taking into account this standardization process, the Radiocommunication Sector of the International Telecommunication Union (ITU-R) has defined three scenarios that could be enabled by 5G NR: Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) and Massive Machine Type Communications (mMTC) [2].

Since the possible applicable scenarios are quite different, specific relevant requirements are expected for each case. The classic information and entertainment media delivery scenario, eMBB, will overcome the barrier of a Gbps per average user inside the coverage area, with possible higher peak data rates. In the case of URLLC systems, latency is considered a critical aspect, this is why, one millisecond of end-to-end latency is established as a reference. Finally, it is expected to increase

the connection density up to $10^6/\text{km}^2$ for mMTC environments [2].

The deployment of 5G communication systems within new environments will enhance the spectral efficiency. However, in order to achieve all the objectives, 5G has to be complemented with other techniques that allow a considerable increase in the spectrum efficiency. Several interesting techniques have been presented in the recent literature and, specifically, NOMA is considered one of the most promising.

As described in [3], NOMA could be based on a layered transmission structure to transmit simultaneously multiple different services with different power and robustness levels. In NOMA, the whole bandwidth during the 100% of the time is used to transmit at least two services. That is why, NOMA is usually presented as a technique that improves the overall spectral efficiency when compared with more classic approaches.

In addition, a more relevant and recent example of the successful implementation of this technology was the acceptance of Layered Division Multiplexing (LDM), a low complexity version of NOMA, as a Physical Layer (PHY) baseline technology for ATSC 3.0 [4]. In LDM, on the one hand, a robust Core Layer (CL) is transmitted for portable and handheld receivers to deliver mobile services in indoor conditions. On the other hand, an Enhance Layer (EL) is designed to deliver high data rate services, such as UHD TV or multiple HDTV services to fix terminals.

In this paper, the authors propose to introduce NOMA as part of the 5G NR Release 15 physical layer. Consequently, services with unbalanced capacity requirements could be simultaneously offered with increased spectrum efficiency. In addition, depending on the use case, this efficiency increase can be turned into a throughput gain, reliability gain or both at the same time. In short, the introduction of NOMA can be turned into a more flexible configuration, which means a wider range of possible implementable PHY configurations.

The paper is organized as follows. Section II describes the related work that has been developed about this topic. Section III provides the definition of the combination of NOMA with eMBMS systems. Moreover, Section IV describes the evaluation system and the proposed use cases. Then, Section V presents the obtained results and, finally, conclusions are described in Section VI.

II. RELATED WORK

Nowadays, 5G is a hot topic inside every communications forum. This fifth generation is supposed to be the solution to face the latest communication challenges and the final convergence tool for the cooperation of a wide range of communication systems. The first version of 5G, Release 15, corresponds to NR Phase 1, where there are common elements between LTE-A-Pro and NR, such as Orthogonal Frequency Division Multiplexing (OFDM). However, in this phase a very relevant scenario has not been considered yet: the point-to-multipoint (PTM) audiovisual content distribution.

In fact, the European Commission (EC) has recently funded an international research project to work in this area, namely 5G-Xcast [5]. Its main objective is to develop capabilities for 5G broadcast and multicast PTM systems. In order to achieve that goal, as presented in [6], new levels of network management and delivery cost-efficiency are considered. The paper also discusses the implications of PTM for network slicing, to customize and optimize network resources on a common 5G infrastructure to accommodate different use cases and services taking into account the user density. Although this project has presented different alternatives to enable broadcasting in 5G environments, NOMA has not been considered.

In [7], a two-layer architecture is proposed based on a transceiver architecture for LTE-A-Pro. In order to compare both technologies, some results are presented for specific Modulation and Coding Scheme (MCS) values. However, despite the high compatibility that exists between LTE-A-Pro and 5G NR, this approach is not including a fully compatible transceiver with Release 15. For instance, the newly designed LDPC/Polar codes are not implemented, and it must be taken into account, that the efficiency of the Forward Error Codes (FEC) is a critical parameter for the performance of NOMA. Therefore, the performance curves are not completely applicable for Release 15 and the reliability increase that newly designed LDPC/Polar codes offer is not included.

To our best knowledge, this paper is the first comprehensive analysis of the 5G NR in combination with NOMA techniques. Hence, by this analysis, firstly, we are proposing a NOMA-based communication system for enabling broadcasting in 5G that is very close to the specifications of the standard. Secondly, Bit Error Rate (BER) vs. SNR performance curves are presented for two scenarios for both, 5G NR systems and NOMA over 5G NR systems.

III. 5G EMBMS USE CASE

Implementing broadcasting within broadband cellular network technologies (3G/4G) has always been a challenge. Thus, implementing it on 5G platform will not be straightforward. Traditionally, the most popular alternative has been Multimedia Broadcast Multicast Services (MBMS) technology and its subsequent evolutions.

The first standardization phases of MBMS appeared in UMTS Release 6, before any 4G specification. However, it was not included in the first LTE version. In fact, in Release 9 a slightly different version was approved, which was called

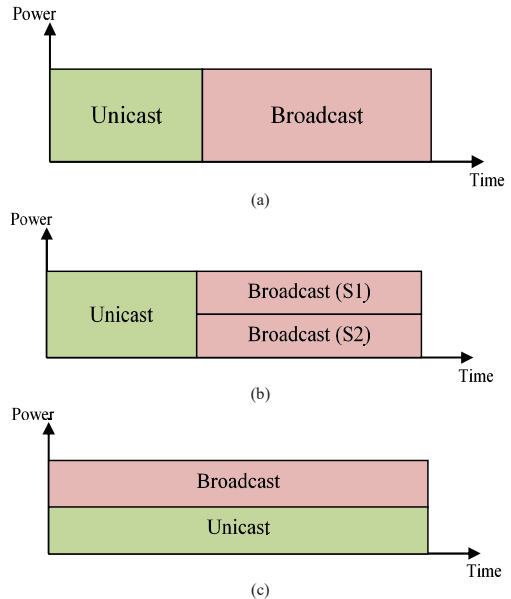


Fig 1. eMBMS representation: (a) only eMBMS, (b) eMBMS and NOMA, (c) NOMA instead of eMBMS

Evolved MBMS (eMBMS). A simplified eMBMS representation is shown in Fig. 1(a). Taking into account this background and the proposed roadmap for 5G NR, a similar version of the actual eMBMS is expected to be implemented in future releases (probably in Rel' 17, since Rel' 16 does not include PTM communications).

Regarding NOMA and its interoperability with eMBMS ecosystems, several works have been carried out based on LTE or theoretical 5G approaches, [8] to [10]. Therefore, it is the appropriate time to integrate NOMA in 5G NR and enable point to multipoint services with better efficiency. The main difference with traditional eMBMS is the multiplexing philosophy, since, while current eMBMS is based on Time Division Multiplexing (TDM) and could be complemented with frequency division; NOMA is based on power division.

If NOMA is adopted as a multiplexing complementary alternative for the existing eMBMS system, a combination of time-power division will be done, as it is represented in Figure 1.b. In this case, firstly, resources are time domain divided for unicast services and for broadcast/multicast services. Hence, in the first part of the frame, a time division will be applied, and unicast services will be transmitted. In addition, in the second part of the frame, time division is not needed again and the broadcast/multicast services will be transmitted overlaid in several layers. In Fig. 1(b), two different services are overlapped, S1 and S2.

However, if NOMA is laid out as a replacement of multiplexing technologies in 5G, exclusively a power domain

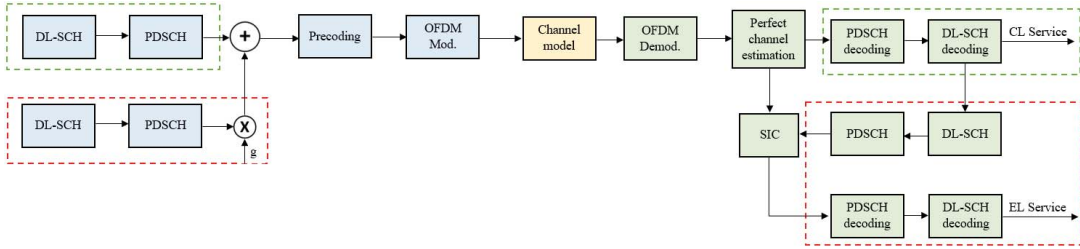


Fig 2. General block diagram of the transceiver architecture

division can be done, and any time or frequency division would be complementary. For instance, a common broadcast service could be delivered in the CL for all the users in the cell, and the rest of the unicast services will be transmitted in the EL, applying time division to share the RF resources among the users. A summarizing diagram is shown in Fig. 1(c) for a simple two-layer scenario.

These proposals can come with an increase in the offered throughput due to the reorganization of the streams and a better exploitation of the resources. Nevertheless, because of the power division that NOMA assumes, the required threshold to decode successfully each of the MCS suffers a penalty.

IV. NOMA-BASED 5G NR

In this section, the developed simulation tool is presented. Firstly, the simulation set-up will be described taking into account the implemented modules, and, secondly, the two proposed use cases are presented.

A. Simulation Set-up

A transmitter and receiver chain has been implemented in Matlab. This prototype is fully compliant with the 5G NR Release 15 PHY standard. It is important to highlight that in this work a Physical Downlink Shared Channel (PDSCH) channel has been implemented because 5G NR does not include a specific broadcast channel. However, the proposed transceiver chain is fully compliant with a generic broadcast channel, and, therefore, if broadcast services were included in Release 17 or Release 18, this proposal would be applicable. Afterwards, several modifications have been introduced in the transceiver blocks in order to introduce NOMA multiplexing capabilities. A block diagram of the transceiver architecture is shown in Fig 2, where blue blocks are transmitter modules and green modules are receiver modules.

First, two independent data flows are created, one for the CL (green dashed box on the left) and the other one for the EL (red dashed box on the left). In each of the data flows, Downlink Shared Channel (DL-SCH) transport channel coding is applied and the PDSCH is generated. Then, the EL symbols are attenuated by applying an injection level, g . The injection level defines the power level of the EL signal relative to the CL signal. Since the CL signal is designed to have higher power, g has a real value in $[0, 1)$, where $g = 0$ results in a single-layer system [3]. After having superposed both

signals, the NOMA ensemble is normalized and a precoding is applied before the grid is calculated. Finally, the last step in the transmitter side is the OFDM framing.

Once the transmitter has finished each of the modules, the channel model is applied. In this case, the AWGN channel is proposed, since it is the first approach to evaluate this proposal.

The first step in the receiver side is to demodulate the OFDM signal, in which perfect synchronization is assumed. Concerning the channel estimation, perfect channel estimation is also considered. At this reception point, since the low-power EL service is treated as an additional interference in the CL decoding process, the CL service is obtained just decoding PDSCH and DL-SCH. However, in order to decode the EL service a signal cancellation is applied (SIC module in Fig 2). The input signals for the SIC module are: the received signal and the obtained CL re-modulated again. Finally, the EL service is obtained decoding PDSCH and DL-SCH from the SIC output.

Undoubtedly, the introduction of NOMA schemes increases the receiver complexity. However, drawbacks only affect the EL. In fact, CL is obtained by following a fully compliant receiver chain. Therefore, it is just the EL service the one that is affected by the complexity increase.

For each simulation set, 30 kHz subcarrier spacing with SISO configuration has been considered, within a 10 MHz RF channel. In addition, a normal Cyclic Prefix (CP) length is assumed. Therefore, the CP duration is $2.34 \mu\text{s}$ per each OFDM symbol, which has a total length of $35.68 \mu\text{s}$.

Finally, regarding Medium Access Control (MAC) layer and above layers, Hybrid Automatic Repeat Request (HARQ) retransmission schemes are disabled in this paper. Although HARQ schemes could improve the overall communication system reliability performance, the complexity needed in order to introduce NOMA will be also increased, and so, it is not considered in this first approach. Therefore, the results shown in this work are evaluating the performance of a 5G NR fully compliant PHY layer.

B. Use Case 1: Only Broadcast Mode

In this case, NOMA is configured for conveying two broadcast media contents in the same RF channel. In addition to that, the use of Scalable Video Coding (SVC) techniques is considered.

TABLE I. CONFIGURATION FOR USE CASE 1

NOMA (IL = -5 dB)		TDMA (50%-50%)	
Configuration	Capacity (Mbps)	Configuration	Capacity (Mbps)
UL	MCS 1 QPSK 193/1024	Mobile (I)	MCS 2 QPSK 308/1024 2.9
		Mobile (II)	MCS 3 QPSK 449/1024 4.3
LL	MCS 8 16QAM 553/1024	Fixed (I)	MCS 16 64QAM 719/1024 20.5
		Fixed (II)	MCS 17 64QAM 772/1024 22.0

TABLE II. CONFIGURATION FOR USE CASE 2

NOMA (IL = -14 dB)		TDMA (75%-25%)	
Configuration	Capacity (Mbps)	Configuration	Capacity (Mbps)
UL	MCS 12 64QAM 517/1024	Fixed (I)	MCS 15 64QAM 666/1024 28.4
		Fixed (II)	MCS 16 64QAM 719/1024 30.7
LL	MCS 6 16QAM 434/1024	IoT (I)	MCS 24 256QAM 841/1024 16.0
		IoT (II)	MCS 25 256QAM 885/1024 16.8

Therefore, the first service (CL) should guarantee the delivery of at least one HD service to mobile receivers [11], so the targeting capacity should be between three and five Mbps. For this service, low SNR threshold values are expected. The second service is simulating the transmission of a 4K/8K content to fixed receivers. Receivers will enhance the CL service by the use of SVC in order to obtain higher quality content. In challenging reception conditions, fixed receivers will always decode the CL service. In this case, for the EL, the targeting SNR threshold should be higher and the desired data rate is around 20Mbps [12].

Moreover, the exact transmitted capacities have been obtained by implementing real 5G NR MCS values (obtained from Table 5.1.3.1-2 in [13]), they are shown in TABLE I. This capacity values have been calculated for a 10MHz channel bandwidth.

In relation with eMBMS environments, this use case represents an example for the Fig 1.b, where NOMA is applied to deliver two broadcast services. In this case, both broadcast services are not completely uncorrelated, because EL will enhance the CL layer service if the reception is without errors. Moreover, the complexity increment derived from the implementation of NOMA techniques (mentioned in Section IV.A) only affects fixed receivers. In the case of mobile receivers, the existence of the EL is completely transparent.

C. Use Case 2: Mixed Mode

In this use case, NOMA is implemented to deliver broadcast and unicast services, therefore a mixed transmission mode it is assumed. For this case, services are considered independent and they are targeting different receivers.

On the one hand, the CL is configured for addressing the broadcast requirement. Fixed receivers will receive 4K/8K content, so, around 30 Mbps have to be delivered [14]. Correct reception must be guaranteed to 99% of receivers, and, therefore, reliability is considered a critical aspect.

On the other hand, the EL is configured to deliver unicast services based on IoT for smart traffic management. In this case, the EL is used to deliver on demand traffic information to IoT devices. Although a standard quality service is

considered for this kind of users, RF resources should be distributed among the users that require EL services. That is why, higher capacity has to be offered in comparison with the service requirement. In this case, around 16 Mbps are going to be transmitted. Therefore, in the case of 160 devices connected simultaneously to the same transmitter, at least, 100 kbps are received in each device.

As in the previous Section, the exact suggested capacities have been obtained by implementing real 5G NR MCS values (obtained from Table 5.1.3.1-2 in [13]). TABLE II summarizes the capacity for each multiplexing technique configuration. This capacity values have been calculated for a 10MHz channel bandwidth.

Comparing this use case with the eMBMS paradigm, this situation should cover the Fig. 1(c) situation, where a common broadcast transmission is delivered in the CL and unicast services are transmitted in the EL. In this case, IoT devices receiving the EL have to cancel the CL service in order to obtain their content. However, for the fixed receivers it does not matter what is transmitted in the EL.

V. RESULTS

A. Use Case 1: Only Broadcast Mode

Results for the only broadcast mode are presented in Fig 3, where CL results are represented in Fig. 3(a) and EL results in Fig. 3(b). In both graphics, a comparison is made between NOMA and TDMA multiplexing schemes performance. In the y-axis the BER value is represented, whereas in the x-axis the SNR value in dBs.

First, in Fig. 3(a), the results for CL services are presented. In a first approach, it seems that NOMA and TDMA I configuration have similar reliability performance. However, it is remarkable that even if MCS 1 by using NOMA and MCS 2 by using TDMA have similar performance (NOMA offers a gain of 0.3 dB for a BER value of 10^{-4}), from the capacity point of view, by using NOMA the transmitted data rate is around 20% higher. Comparing NOMA performance with TDMA II, a gain around 2.1 dB is obtained.

The difference in the capacity values is due to the granularity of the standard configurations for the PHY level.

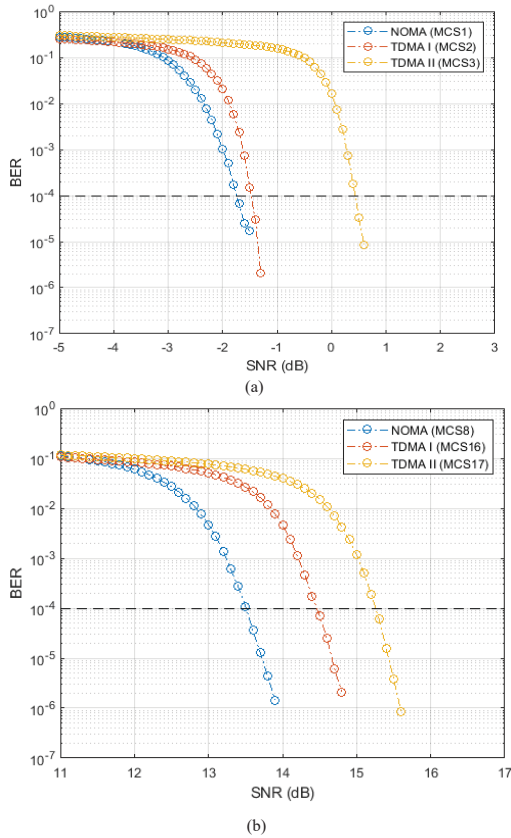


Fig 3. Obtained results for use case 1: (a) NOMA vs. TDMA for mobile service, (b) NOMA vs. TDMA for fix service

Since the number of MCS configurations are limited in the 5G NR standard, capacity values are different for each configuration.

Furthermore, in Fig. 3(b), the results for fix receivers are presented for both, NOMA and TDMA multiplexing schemes. In this case, the results show an interesting performance gain of about 1 dB in comparison with TDMA I, and around 2 dB in relation to TDMA II. This gain is due to the asymmetry between the offered services SNR value. In this case, the gain has been invested in improving the performance by reducing the SNR threshold. However, a similar analysis could be carried out, in which the goal will be to increase the capacity of the fix services.

Therefore, it can be assumed that by using NOMA in an only broadcast mode scenario, reliability gains can be considered for both service types. Adding the obtained gains for both services, more than 4 dB can be obtained.

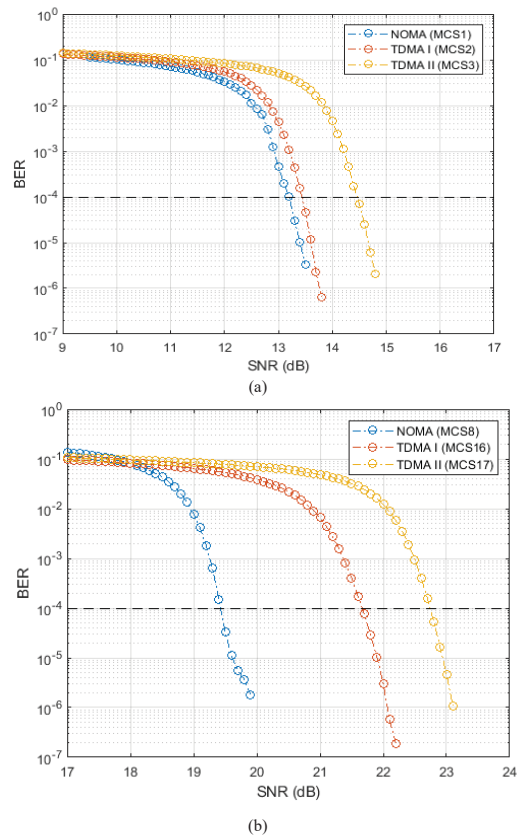


Fig 4. Obtained results for use case 2: (a) NOMA vs. TDMA for fix service, (b) NOMA vs. TDMA for IoT

B. Use Case 2: Mixed Mode

Results for the mixed broadcast/unicast mode are presented in Fig 4, where CL results are represented in Fig. 4(a) and EL results in Fig. 4(b). Graphics maintain the format used in the previous Section.

On the one hand, regarding Fig. 4(a), broadcast services have similar performance behavior in terms of reliability. Although, it is true that NOMA offers slightly better results in comparison with the low capacity TDMA approach (TDMA I), around 0.2 dB; a higher gain is obtained in relation to TDMA II case, where around 1.3 dB are obtained.

However, the similarity in the CL results involves a greater unbalance in the EL results, which are shown in Fig. 4(b). In this case, the use of NOMA will benefit IoT receivers from more than 2 dB SNR gain in comparison with TDMA I configuration. Moreover, more than 3 dB of gain are obtained in relation to TDMA II configuration. Undoubtedly, this gain

is really interesting due to the characteristics of the EL receivers, which should be less efficient than the fixed receivers.

Therefore, finally, the possible application of NOMA for a mixed broadcast/unicast mode is also demonstrated. In fact, up to 4.5 dB aggregated gains are obtained. Moreover, gains could be increased implementing more challenging channels, such as Rayleigh, 0dB Echo or TU-6.

VI. CONCLUSION

This paper presents a novel communication system for broadcasting environments based on the 5G NR Release 15. The theoretical applications obtained including NOMA in a simplified 5G NR architecture are presented in Section III. Afterwards, a fully compliant simulation tool has been developed, presented and evaluated by comprehensively studying two different scenarios.

Results demonstrate that NOMA is a multiplexing scheme that should be taken into account for future releases due to the reliability gain that provides. In the represented use cases, a general behavior has been detected. Firstly, in the CL, slightly better reliability results have been obtained (up to 2.3 dB gain in the first scenario). Secondly, higher gain values are obtained in the EL by using NOMA. In fact, a minimum gain of one dB is presented in the first case, and a maximum gain of three dB in the second case.

To sum up, although a promising technique that offers a wide range of gains has been presented, several improvements should be considered in order to increase the overall performance. That is why, in future works, MAC and upper layers are also going to be taken into account to enhance to whole simulation set up.

ACKNOWLEDGMENTS

This work has been partially supported by the Basque Government under the PREDOC grant program (PRE_2018_1_0344) and by the Spanish Government under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE).

REFERENCES

- [1] TS 38.201, Tech. Spec. Group Services and System Aspects, "NR; Physical layer; General description," V15.0.0, January 2018.
- [2] ITU-R Rec. ITU-R M. 2083-0, "IMT Vision — Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Sept. 2015.
- [3] L. Zhang et al., "Layered-Division-Multiplexing: Theory and Practice," in *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 216-232, March 2016.
- [4] S. Park et al., "Low complexity layered division multiplexing system for ATSC 3.0," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, Mar. 2016.
- [5] D. Ratkaj and A. Murphy, Eds., "Definition of Use Cases, Requirements and KPIs," Deliverable D2.1, 5G-PPP 5G-Xeast project, Oct. 2017.
- [6] J. J. Gimenez, D. Gomez-Barquero, J. Morgade and E. Stare, "Wideband Broadcasting: A Power-Efficient Approach to 5G Broadcasting," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 119-125, March 2018.
- [7] D. Vargas and Y. J. D. Kim, "Two-Layered Superposition of Broadcast/Multicast and Unicast Signals in Multiuser OFDMA Systems" <https://arxiv.org/abs/1811.00912>. Accessed on January 10, 2018.
- [8] J. Montalban et al., "Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 91-95, March 2018.
- [9] L. Zhang et al., "Layered-Division Multiplexing: An Enabling Technology for Multicast/Broadcast Service Delivery in 5G," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 82-90, March 2018.
- [10] L. Zhang, Y. Wu, W. Li, K. Salehian, A. Florea and G. K. Walker, "Improving LTE eMBMS system spectrum efficiency and service quality using channel bonding, non-orthogonal multiplexing and SFN," 2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Nara, 2016, pp. 1-8.
- [11] L. Zhang et al., "Using Layered-Division-Multiplexing to Deliver Multi-Layer Mobile Services in ATSC 3.0," in *IEEE Transactions on Broadcasting*, vol. 65, no. 1, pp. 40-52, March 2019.
- [12] J. Lee et al., "Efficient Transmission of Multiple Broadcasting Services Using LDM and SHVC," in *IEEE Transactions on Broadcasting*, vol. 64, no. 2, pp. 177-187, June 2018.
- [13] 3GPP TS 38.214 v15.3.0, Tech. Spec. Group Services and System Aspects, "NR; Physical layer procedures for data (Release 15)", Sept. 2018
- [14] 3GPP TS 22.261 v15.7.0, Tech. Spec. Group Services and System Aspects, "Service Requirements for the 5G System; Stage 1, "Rel. 15; Dec. 2018.

3.1.2 Aldizkari-artikulua (A1)

Azpiatal honek 1. kontribuzioari buruzko aldizkari-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- E. Iradier, J. Montalban, L. Fanari, P. Angueira, L. Zhang, Y. Wu and W. Li, "Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks," in IEEE Transactions on Broadcasting, vol. 66, no. 2, pp. 503-514, June 2020, doi: 10.1109/TBC.2020.2981759.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 69/266 (Q2) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,419

Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks

Eneko Iradier¹, Student Member, IEEE, Jon Montalban¹, Member, IEEE,
Lorenzo Fanari, Student Member, IEEE, Pablo Angueira, Senior Member, IEEE,
Liang Zhang², Senior Member, IEEE, Yiyang Wu, Fellow, IEEE,
and Wei Li², Member, IEEE

Abstract—This paper addresses the challenge of broadcast and unicast convergence by proposing a PHY/MAC (Physical Layer/Medium Access Control) architecture for 5G New Radio (NR). The solution is based on Power domain Non Orthogonal Multiple Access (P-NOMA). The main PHY/MAC configuration parameters have been analyzed theoretically and their impact on the service configurations is presented in this manuscript. The system concept has been translated into a prototype model and different evaluation tests are presented. First, simulations show that the PHY layer performs better than Time Division Multiplexing/Frequency Division Multiplexing (TDM/FDM) choices of current broadband access systems. Second, performance tests using a network simulation tool are described. The results for capacity, latency and reliability demonstrate that the proposed solution offers an excellent broadcast/unicast convergence choice with significant gain values with respect to legacy PHY/MAC alternatives.

Index Terms—5G, broadcast, convergence, LDM, MAC, NOMA, P-NOMA, unicast.

I. INTRODUCTION

THE STANDARDIZATION process required to create and enhance the fifth generation of mobile communications (5G), which is expected to cover all the increasing connectivity necessities [1], is ongoing. In fact, the first Release (Rel-15) of 5G has already been published, including New Radio (NR) [2], and several improvements in different levels of the protocol stack make this solution a proper alternative for different use

Manuscript received December 1, 2019; revised March 2, 2020; accepted March 3, 2020. Date of publication April 14, 2020; date of current version June 5, 2020. This work was supported in part by the Basque Government (Project IOTERRAZ) under Grant KK-2019/00046 ELKARTEK 2019, Grant IT1234-19, and the PREDOC Grant Program PRE_2019_2_0037, and in part by the Spanish Government (Project PHANTOM) under Grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE). (Corresponding author: Eneko Iradier.)

Eneko Iradier, Jon Montalban, Lorenzo Fanari, and Pablo Angueira are with the Department of Communications Engineering, University of Basque Country (UPV/EHU), 48013 Bilbao, Spain (e-mail: eneko.iradier@ehu.es; jon.montalban@ehu.es; lorenzo.fanari@ehu.es; pablo.angueira@ehu.es).

Liang Zhang, Yiyang Wu, and Wei Li are with the Department of Wireless Communications, Communications Research Centre Canada, Ottawa, ON K2H 8S2, Canada (e-mail: liang.zhang@canada.ca; yiyang.wu@canada.ca; wei.li@canada.ca).

Color versions of one or more of the figures in this article are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TBC.2020.2981759

0018-9316 © 2020 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See <https://www.ieee.org/publications/rights/index.html> for more information.

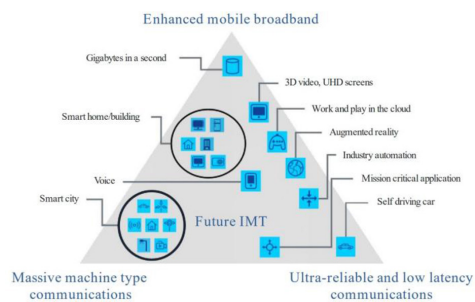


Fig. 1. 5G NR applications and use case families [3].

cases. One of the most relevant contributions can be considered the development of a flexible Physical Layer (PHY) that can be implemented in several scenarios with completely different requirements. It should also be mentioned that Low-Density Parity-Check (LDPC) codes are introduced to enhance the communication reliability.

The Radiocommunication Sector of the International Telecommunication Union (ITU-R) has divided the entire application frame into three use case families: enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC) [3]. In Fig. 1, a summary of the use case families is shown with some other more specific applications.

Each one of the different use case families shown in Fig. 1 has different requirements. In eMBB, which is related to the classic information and entertainment media delivery scenario, high data rates are required. In fact, it is expected to guarantee peak data rate values close to 10 Gbps for the uplink and 20 Gbps for the downlink and support speeds up to 500 km/h. In the case of URLLC, as it is oriented to mission-critical communications, reliability and latency are the most demanded requirements. In fact, an upper bound of one millisecond of end-to-end latency has been established in the user plane. Finally, concerning mMTC, the network is expected to increase the device density rate to values close to 10^6

devices per km² and increase the battery lifetime to around 10 years.

The combination of the large list of new applications and the configuration flexibility presented in the latest Release gives the opportunity to make 5G the main generic solution for wireless communications. However, a mechanism that could enhance the 5G performance is still missing: Point-to-Multipoint (PTM) communications. Although it is true that broadcast/multicast communications are not considered in this first version, they will probably be integrated in future Releases (Rel-17/18).

In parallel to the integration of PTM communications, the convergence between unicast and broadcast services is still an open issue. In 4G systems, Evolved Multimedia Broadcast Multicast Services (eMBMS) has been implemented, which is based on Time Division Multiplexing (TDM) and is complemented with Frequency Division Multiplexing (FDM).

This paper proposes a different standpoint to replace or to complement eMBMS by means of Non-Orthogonal Multiple Access (NOMA) techniques.

As described in [4], a layered division or power-based NOMA can be implemented in order to deliver simultaneously different services, assuming diverse power levels and configurations. The main advantage of P-NOMA systems is that the 100% of the RF bandwidth is used during the 100% of time to transmit two (or more) services. That is why NOMA is considered a spectral efficiency friendly technique when compared with orthogonal multiplexing access solutions, such as TDM or FDM.

The main example of the success of P-NOMA systems is the acceptance of a low complexity P-NOMA structure, Layered Division Multiplexing (LDM), to be part of the Advanced Television Systems Committee (ATSC 3.0) PHY layer baseline technology [5]. In this case, a robust configuration is implemented in the Upper Layer (UL), oriented to portable and mobile receivers. On the other hand, in the Lower Layer (LL), a high capacity configuration is chosen to deliver high data rate services, such as Ultra High Definition Television (UHDTV) or multiple High Definition Television (HDTV) services, to fixed receivers.

The main objective of this paper is to propose, design and evaluate a novel solution for enabling broadcast/unicast service convergence in 5G networks based on P-NOMA. Afterwards, the main implications of this architecture are presented as well as implementation guidelines based on a prototype. Finally, the prototype is evaluated at PHY level using an upgraded network simulation tool. PHY and network layer results are shown and analyzed, separately.

In summary, the technical contributions of this paper include:

- 1) Full architecture definition of a P-NOMA solution for 5G NR at PHY/MAC (Medium Access Control) level. Some blocks of the architecture are novel and critical for the overall performance of the proposal.
- 2) Design and implementation of a frame adaptation layer to combine UL and LL MAC packets.
- 3) Performance evaluation and gain analysis of the proposed technique over different propagation channels.

- 4) Presentation of network level simulations and reliability, latency and capacity analysis.

The rest of the paper is organized as follows. The next section describes related work published up to now on this topic. Section III is focused on overview of 5G NR at different levels. In Section IV, NOMA-based 5G model is presented, taking into account the implications and the proposed novelties. Then, in Section V, a PHY level evaluation of the proposed solution is carried out. In Section VI, the proposed solution is tested in a network simulation tool. Finally, Section VII contains the conclusions and the future works.

II. RELATED WORK

A. Broadcast/Unicast Convergence

5G is expected to be the global wireless solution to guarantee convergence and cooperation between different networks, devices and technologies [6]. However, in its first version, Rel-15, a fundamental scenario, especially for eMBB communications, has not been considered: PTM communications.

The broadcast implementation roadmap in 5G has similar milestones when compared to 4G. Although a broadcast traffic distribution alternative was already included in 3G systems within Multimedia Broadcast Multicast Services (MBMS), it was not until Rel-9 that the first broadcast transmission capabilities were introduced. In fact, in 4G, a slightly enhanced solution was presented (evolved MBMS, eMBMS), which brought higher and more flexible data rate configurations, single frequency network (SFN) operations and carrier configuration flexibility [7]. Latest enhancements applied to eMBMS were included in Long Term Evolution (LTE) Rel-14. One of the most relevant differences was that the limitation of the maximum of 60% of radio resources for broadcast transmissions was removed [8]. In addition, support for eMBMS will be introduced for NR mainly for public safety use cases, Vehicle-to-everything (V2X) applications and railways, and therefore, further enhancements will come in Rel-16 [9].

Concerning the future of broadcast in 5G, the most relevant contributions are related to the 5G-Xcast project [10]. 5G-Xcast was an international research project, funded by the European Commission (EC) that started in June 2017. This project presented a cross-layer PTM proposal at different architecture levels. Among other contributions in 5G-Xcast project, in [11], a specific approach of the 5G NR PHY for terrestrial broadcast was presented. In this paper, the critical parameters of the waveform generation are discussed and the NR-based MBMS solution is compared with the latest LTE Rel-14 version. Aiming to cover a different perspective, in [12], the network slicing concept is discussed within the 5G paradigm. The main implications are detailed in order to optimize the network resources of a particular 5G infrastructure over different PTM use cases.

B. NOMA for 5G Systems

P-NOMA-based systems such as LDM, have demonstrated very positive spectral efficiency properties and an excellent performance for broadcast applications [4]. Nevertheless,

LDM has not been so successful for broadband communication systems and although NOMA was adopted by 3GPP Rel-14, it has not been implemented so far. However, several works presented P-NOMA-based solutions as relevant candidates for broadcasting in 5G [13]–[18].

One of the first works that evaluated the use of P-NOMA within eMBMS is reported in [13]. In this paper, several scenarios where LDM could take advantage of its efficiency increase were presented and the theoretical Signal-to-Noise Ratio (SNR) thresholds for different injection level (IL) values were provided. Some other works evaluated the theoretical interoperability of P-NOMA with the eMBMS ecosystem [14], [15]. While [14] studies the use of LDM as a key technology for 5G networks to deliver PTM transmission within the broadband systems, the authors in [15] present NOMA as a candidate to carry out multicast transmissions in subgroup oriented communications.

Concerning non-theoretical contributions, in [16], the transmission of unicast and broadcast services at the same time in a SFN by using LDM were analyzed. In this case, the study was based on measuring the power consumption per base station. The results provide power savings simultaneously for unicast and broadcast transmissions due to the larger bandwidth available. In [17], P-NOMA was proposed in combination with TDM schemes to deliver mixed broadcast and unicast services in a 5G-MBMS environment. The performance and the implications of using P-NOMA for both services, broadcast and unicast, were presented and evaluated. Results indicate that significant capacity gains could be achieved when using P-NOMA in 5G NR. However, the only Key Performance Indicator (KPI) evaluated is capacity, while latency and reliability are not taken into account. Finally, in [18], the first NOMA-based 5G NR PHY layer transceiver was presented. The prototype was tested by implementing a convergence-oriented use case. Results offer significant capacity gains in different configurations. However, the AWGN channel was the only simulation case and the impact of retransmissions (Hybrid Automatic Repeat Request, HARQ) was not evaluated.

III. 5G OVERVIEW

As in 4G, 5G NR PHY is based on Orthogonal Frequency Division Multiplexing (OFDM) technique. However, one of the main novelties of this standard is not the base technology, but its configuration flexibility. There are five different numerologies (μ) available with different subcarrier spacing (SCS) values obtained from the following expression:

$$SCS(kHz) = 15 \cdot 2^\mu \quad (1)$$

where μ represents the numerology and it can be 0, 1, 2, 3 or 4.

In NR, each radio frame has a fixed length of 10 ms and it is composed of a fixed number of ten subframes. Moreover, each subframe has a duration of one millisecond. The number of slots per subframe varies depending on the numerology that is implemented. In TABLE I, a summary of the possible number of slots per subframes and their duration is presented as a function of the numerology. In comparison with 4G, this

TABLE I
5G NR SUBCARRIER SPACING INFLUENCE

μ	SCS (kHz)	# Slots/Subframe	Slot (ms)
0	15	1	1
1	30	2	0.5
2	60	4	0.25
3	120	8	0.125
4	240	16	0.0625

TABLE II
OFDM SYMBOLS

	$\mu = 0$	$\mu = 1$	$\mu = 2$	$\mu = 3$	$\mu = 4$
OFDM Symbol (μ s)	66.67	33.33	16.67	8.33	4.17
CP (μ s)	4.69	2.34	1.17	0.57	0.29
Total length (μ s)	71.36	35.67	17.84	8.90	4.46

aspect is considered a relevant difference. In addition, although the default number of symbols per slot is 14, different configurations can be implemented. On the one hand, in order to enable the transmission of short data packet, a mini-slot configuration has been introduced in the standard, where 2, 4 or 7 symbols can be allocated. On the other hand, just with the opposite aim, slots can be gathered for longer transmissions.

Another variable that can be tuned is the OFDM symbol length. TABLE II presents the OFDM symbol lengths with and without the Cyclic Prefix (CP). As shown, the shortest OFDM symbol lengths allow their transmission in less than 5 μ s. In consequence, the highest numerologies, especially $\mu = 3$ and $\mu = 4$, are designed to address URLLC by using shorter transmission durations.

Finally, the main PHY level novelty from the reliability point of view is the new channel coding. NR does not include Turbo-codes; LDPC and Polar codes are supported. Polar codes are reserved for control packet transmissions and LDPC codes are used in payload data packets. Indeed, LDPC codes have demonstrated to be a very robust channel coding technique and their reliability is very close to the Shannon limit, just half a dB away [19], [20].

Regarding the MAC layer implemented in NR, several characteristics have been directly inherited from LTE: the mapping process between logical and transport channels, the multiplexing/demultiplexing of MAC Service Data Units (SDU) when required, etc. Moreover, as in LTE, HARQ techniques are used for error correction. 5G NR HARQ are error correction techniques based on packet retransmissions. The main difference when compared with 4G is that the timing between data transmission and the HARQ response is flexible. While in 4G timing was fixed to 4 ms, in 5G the number of time slots between data transmission and the HARQ response can be dynamically adapted for enabling lower latencies.

Another aspect that has been modified in NR is the resource management. As shown in Fig. 2, the smallest unit that appears in the resource grid is the Resource Element (RE), which consists of one subcarrier and one OFDM symbol, in frequency and time domain, respectively. However, the Resource Block (RB) concept is not the same as in 4G. In NR, RBs are defined as 12 consecutive subcarriers in one OFDM symbol. Then, as presented in TABLE III, the minimum and

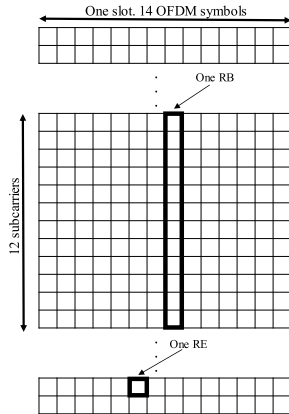


Fig. 2. Basic resource management terminologies.

TABLE III
RESOURCE BLOCKS AND BANDWIDTH SIZES

μ	RB _{MIN}	RB _{MAX}	BW _{MIN} (MHz)	BW _{MAX} (MHz)
0	24	275	4.32	49.5
1	24	275	8.64	99
2	24	275	17.28	198
3	24	275	34.56	396
4	24	138	69.12	397.44

maximum bandwidths were defined for each of the possible numerologies (from 4.32 MHz to 397.44 MHz). Finally, the amount of RBs required to obtain the bandwidth ranges was calculated according to each numerology and bandwidth range by dividing the bandwidth by the size of one RB.

IV. 5G-NOMA

In this section, the implications of introducing NOMA in the 5G PHY are presented. First, the general structure is introduced and then, several issues regarding the implementation are explained.

A. General Structure

In the first phase of this work, a transceiver has been developed in MATLAB. This prototype is partially compliant with the NR Rel-15 standard. A Physical Downlink Shared Channel (PDSCH) has been implemented in the prototype, since 5G NR does not include any specific broadcast channel for data delivery. Nevertheless, the prototype is compatible with any future broadcast channel that could be introduced in the future (Rel-17/18). In addition, in order to introduce NOMA in the 5G NR transceiver some modifications have been done. In Fig. 3, a general block diagram of the overall transceiver is shown. The blocks related to the transmitter are color coded in orange, while receiver blocks are painted in blue.

At the beginning of the transceiver, two independent data flows are created, one per each NOMA layer. The blocks related to UL are located inside the green dashed box, while

the blocks related to the LL are inside the red dashed box. A Downlink Shared Channel (DL-SCH) transport channel is generated for each layer, and then, the DL-SCH is encapsulated into PDSCH, where the modulation and the LDPC coding is applied. The LDPC codeword size is adapted depending on the modulation and code rate that is used.

Once PDSCH are generated for both layers, they are combined into a single NOMA signal ensemble. Therefore, symbols corresponding to the LL are attenuated by a predefined IL (g , in Fig. 3, expressed in linear units). The IL indicates the relative power distribution between both layers, so g has a real value within the range $[0, 1)$, where $g = 0$ results in a single-layer system and $g = 1$ results in a two-layer system with equal power distribution [4]. The IL can also be expressed in dBs ($IL = 10 \cdot \log(g)$). Then, the UL and the attenuated LL are added creating the definitive NOMA signal ensemble. After superimposing both layers, the output constellation is normalized. Finally, the precoding matrix for the next transmission is calculated using singular value decomposition (SVD). Then, the OFDM signal is generated.

The transmitted signal is filtered through the channel model block. In this case, two channel model families have been integrated: an ideal channel-fading model with Additive White Gaussian Noise (AWGN) and a Tapped Delay Line (TDL) [21]. The first will be used as a reference to test the prototype and define the PHY configurations, while the second one is implemented as a more realistic and challenging channel model. TDL channel models are defined for the full frequency range and for non-MIMO transmissions. They are composed by several taps with different delays and amplitudes. Five different channel profiles are defined, where TDL-A, TDL-B and TDL-C represent channel models for Non-Line of Sight (NLOS) conditions and TDL-D and TDL-E are aimed for Line of Sight (LOS) conditions [21]. More details are presented about the parameters of the implemented channel models in Section V.

At the receiver, the first modules perform OFDM demodulation and channel estimation. The channel estimation block also removes the precoding information from the channel estimation. Then, for UL recovery, demodulation and LDPC decoding is applied at PDSCH and DL-SCH blocks. The UL noise threshold is low and in consequence, the lower layer will be assumed as additional noise for the UL. In order to recover the LL, a Successive Interference Cancellation (SIC) module has been introduced. Since this module takes as input the received signal and the regenerated UL, the DL-SCH and the PDSCH modules have to be applied again to re-create UL bits. The output of the SIC module is the difference between both signals, i.e., the received LL. Hence, to obtain the definitive transmitted LL bits, PDSCH decoding and DL-SCH decoding is applied to the output of the SIC module.

In parallel to the complete 5G-NOMA architecture, HARQ retransmission schemes are also implemented. In this case, when the UL data and the LL data are obtained in the DL-SCH decoding module, received packets are checked. If the packet is received successfully, a new transport block is generated and transmitted. However, if errors occur, a retransmission is scheduled by changing the Redundancy Version (RV) value.

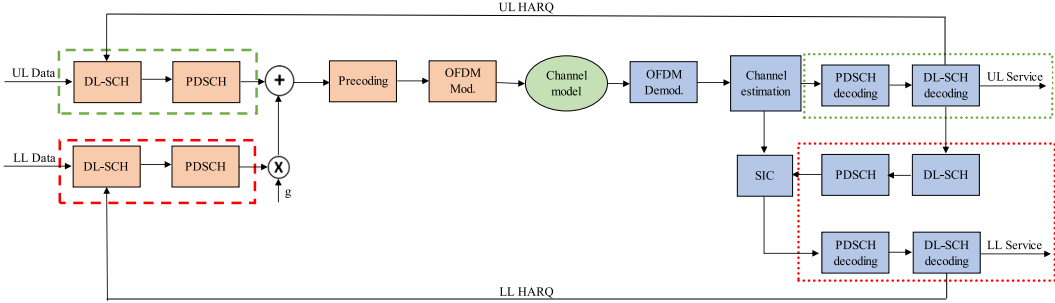


Fig. 3. Simplified general block diagram of the transceiver architecture.

In the proposed 5G NOMA implementation, HARQ processes are independently carried out in each layer.

Finally, it is important to highlight complexity aspects. It is true that introducing NOMA techniques in the 5G NR standard, the complexity of the transceiver will be increased. However, this complexity drawback does not affect the complexity of receivers only intended for the UL decoding. In fact, as it can be seen in Fig. 3, the UL decoding chain follows the traditional modules. Therefore, only the receivers interested on recovering LL suffer from extra complexity increase associated to the SIC module.

B. Frame Adaptation Layer

Although UL and LL data flows are independently configured, a joint framing management is needed. Indeed, when the NOMA signal ensemble is created, the inputs to both layers must have the same length. That is why, a new adaptation layer between the MAC and the PHY is required. The frame adaptation layer is based on the following expression:

$$\#SC_{UL} = \#SC_{LL} \quad (2)$$

where $\#SC_{UL}$ and $\#SC_{LL}$ are the number of subcarriers allocated for the transmission in the UL and in the LL, respectively. This parameter defines the amount of coded bits that can be transmitted:

$$\#SC_{UL} = \frac{tx\ bits_{UL}}{m_{UL}} = \frac{tx\ bits_{LL}}{m_{LL}} \quad (3)$$

where $tx\ bits$ is the amount of bits that are introduced in the modulator and m is the modulation index. Finally, the amount of transmitted bits is calculated from the following relation:

$$\#SC_{UL} = \frac{info\ bits_{UL} \cdot CR_{UL}}{m_{UL}} = \frac{info\ bits_{LL} \cdot CR_{LL}}{m_{LL}} \quad (4)$$

where $info\ bits$ are the PHY transport block bits and CR is the implemented code rate. Assuming a fixed amount of information bits for the UL, the amount of information bits for the LL in each frame is calculated from the following expression:

$$info\ bits_{LL} = \frac{info\ bits_{UL} \cdot CR_{UL} \cdot m_{LL}}{m_{UL} \cdot CR_{LL}} \quad (5)$$

Therefore, the length of the LL packet received from the MAC layer is restricted by the combination of the modulation order and the code rate (Modulation and Coding Scheme, MCS) of each layer and the length of the UL MAC packet.

Simulations use complete time slots so the number of subcarriers allocated for each iteration will be driven by SCS and bandwidth choices. In practice, the length of MAC packets will be then set by defining modulation and code rates of UL and LL.

C. Resource Allocation

As described in Section III, one RB is the minimum data unit that can be allocated in 5G NR. Indeed, this resource allocation technique implies frequency domain multiplexing (subcarriers) and time domain multiplexing if more than one RB is gathered. Therefore, P-NOMA can be considered a two dimensional multiplexing technique. In Fig. 4(a), an example of NR Rel-15 resource allocation pattern is shown. Each color represents the one different service or unicast receiver. However, if P-NOMA is introduced in the 5G NR resource allocation mechanism, another parameter should be taken into account when distributing the resource: the transmitted power. In Fig. 4(b), an example of a resource allocation pattern when P-NOMA is implemented is shown. Again, each color represents a different transmitted service. In this case, inside each RB due to the IL, more than one service can be delivered. Therefore, if P-NOMA is introduced in 5G NR, a three dimensional resource allocation should be carried out: time, frequency and power. Undoubtedly, this third dimension increases the number of parameters and possible pattern combinations, and, therefore, higher flexibility when applying the resource allocation.

D. Broadcast/Unicast Convergence

The resource allocation approach presented in Section IV-C presents a new alternative to cover different use cases. In fact, P-NOMA would enable the convergence between broadcast and unicast services in the same RF channel. On the one hand, Fig. 4(c) shows how the broadcast/unicast convergence issue is solved in eMBMS. As it can be seen, broadcast and unicast services are multiplexed by using frequency domain multiplexing, although a similar allocation pattern can be

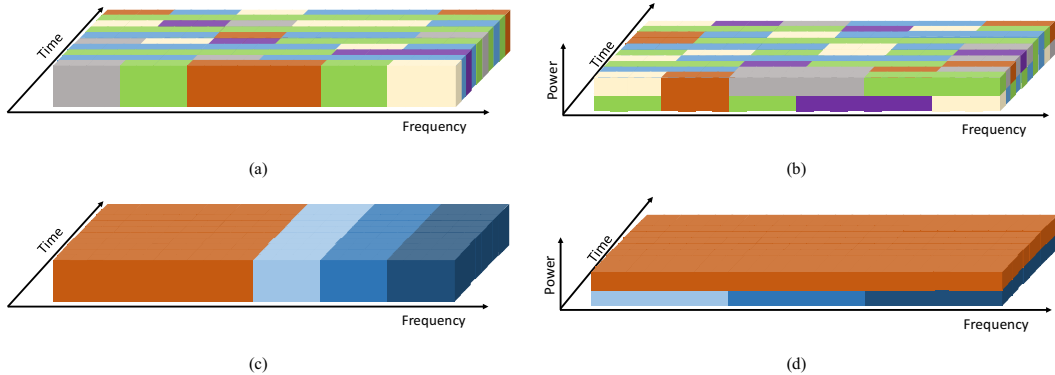


Fig. 4. Resource allocation patterns: (a) generic TDM/FDM, (b) generic P-NOMA, (c) broadcast/unicast convergence solution in TDM/FDM, (d) broadcast/unicast convergence solution in P-NOMA.

obtained if a time domain multiplexing is followed. The dark orange block represents the allocation for the broadcast service, whereas the blue blocks are reserved for different unicast services, where each blue tone represents a specific unicast service. In this case, a 50%-50% time division has been applied between broadcast and unicast services, which means that the available resources are equally shared between broadcast and unicast services. Moreover, concerning the unicast services, three simultaneous services have been assumed with an equal resource sharing among them.

On the other hand, in Fig. 4(d) the broadcast/unicast convergence issue is solved by implementing P-NOMA in the 5G NR resource allocation mechanism. As in Fig. 4(c), dark orange block represents the broadcast service and the blue blocks are different unicast services. In this case, broadcast and unicast services are sharing the same OFDM symbol and the same subcarriers, but they are superimposed with different power levels. The UL is reserved for the broadcast content, whereas the LL is used for delivering unicast services, since traditional broadcast transmissions have to guarantee a high reception rate and so, they have to meet more strict availability requirements. Then, in the LL in order to share the resources among the different unicast services frequency domain multiplexing is used. Therefore, the resource allocation scheme presented in Fig. 4(d), as in Fig. 4(b), implies LDM + FDM (or TDM) multiplexing scheme concatenation. Comparing Fig. 4(c) and 4(d), the latter certainly provides wider available bandwidth for each service, resulting in capacity gain.

When P-NOMA is used to guarantee the convergence between broadcast and unicast services, the main parameter to configure the overall content distribution is the IL. Therefore, the implemented IL value has a direct impact in the delivered services and so, a tradeoff has to be assumed between the characteristics of broadcast and unicast services. For example, if high IL values are selected, higher throughput can be obtained in the UL (or higher reliability) for the broadcast service. However, as the power reserved for the LL is lower, the available capacity will decrease, and less unicast services

could be delivered. On the other hand, if low ILs are selected in order to enhance the unicast services, the reliability of the UL will be reduced and the broadcast coverage area could be noticeably impacted.

V. PHY EVALUATION

This section describes the evaluation of the PHY P-NOMA solution in different propagation channels.

A. Theoretical Approach

A use case with a mixture of broadcast and unicast services has been designed. The broadcast service is 4K UHDTV content delivered on a 30 Mbps bit stream [22]. Availability will be considered a critical factor because correct reception has to be guaranteed to 99% of the receivers at least. On the other hand, in the case of the unicast services, configurations that allow higher data rates have been used. The reference value for unicast services has been set to 50 Mbps, which has to be shared among all the unicast receivers. For this kind of services, the higher the available data rate is, the higher the amount of users that could simultaneously receive the service can be. Some examples of this type of services are: Internet of Things (IoT) for smart traffic management or on demand TV content for mobile receivers.

From a multiplexing standpoint, P-NOMA offers a new dimension for system flexibility and the capacity and robustness requirements posed by each service can be tailored with different time, frequency and power domain adjustments. Examples shown in TABLE IV explain how broadcast services would be delivered in the UL and unicast services in the LL. The values in TABLE IV provide comparison metrics between the expected capacities and thresholds in P-NOMA and TDMA. Capacity is calculated for a NR signal of 20 MHz bandwidth and SNR thresholds are based on AWGN simulations.

The methodology for comparing P-NOMA and TDMA starts setting the service bitrate requirements in TDMA (30 Mbps UHDTV Broadcast content and 50 Mbps

TABLE IV
USE CASES CONFIGURATION

Service	TDMA (50%-50%)			NOMA (I) (IL = -6 dB)			NOMA (II) (IL = -6 dB)		
	MCS	Cap. (Mbps)	SNR _{TH} (dB)	MCS	Cap. (Mbps)	SNR _{TH} (dB)	MCS	Cap. (Mbps)	SNR _{TH} (dB)
Broadcast	12	30.3	11.1	5	29.5	11	5	29.5	11
Unicast	19	51.2	17.5	10	51.4	15.8	12	60.6	18

unicast capacity). The TDMA choices are MCS 12 (64QAM 517/1024 and 3.0293 bps/Hz) and MCS 19 (64QAM 873/1024 and 5.1152 bps/Hz) (according to [23, Table 5.1.3.1-2]).

Then, P-NOMA is adjusted to provide equivalent UL bitrate and robustness (4K UHD TV content). The UL MCS selection is MCS5 (16QAM 378/1024 and 1.4766 bps/Hz) while two possible variants are proposed for the lower layer. NOMA (I) optimizes the system threshold while maintaining capacity (51.4 Mbps vs. 51.2 Mbps) using a LL MCS10 (16QAM 658/1024 and 2.5703 bps/Hz). NOMA (I) configuration provides a 1.7 dB improvement in the LL with respect to the equivalent TDMA threshold. A second optimization case is NOMA (II) that maintains an equivalent threshold (18 dB) with MCS12 (64QAM 517/1024 and 3.0293 bps/Hz) and varies capacity (60.6 Mbps vs 51.2 Mbps). The injection level in P-NOMA has been set to -6 dB to guarantee that the service area of both systems is equivalent.

B. Simulation Results

Once a preliminary analysis based on the AWGN channel has been carried out, more simulations have been performed over different propagation channels in order to widen the results.

Concerning the wireless propagation channel, TDL-D and TDL-E profiles have been implemented. In both cases, the LOS condition is included. Additionally, three different desired delay spread (DDS) values have been simulated for each channel model: 90 ns, 360 ns and 1100 ns. Those values have been selected because they are aligned with short-, normal- and long-delay profiles for an urban environment [21].

Results obtained with the developed transceiver over the detailed channels are presented in Fig. 5. Following those graphics, a performance comparison can be made between P-NOMA and TDMA multiplexing schemes.

From a general perspective, each transmission configuration shows a similar performance over the different channels. In comparison with the AWGN channel, the performance is deteriorated in the range of 0.3 dB and 2 dB. The short-delay and the normal-delay profiles, present very similar results in both cases. It should be highlighted, however, that the long-delay profile channels have stronger negative effects on the received signal and the required SNR thresholds are higher. In fact, the TDL-E channel model is even more challenging in long-delay conditions than the TDL-D.

As expected, services oriented to fixed receivers (TDMA (I) and NOMA (UL)) show a very similar reliability performance. In fact, the difference between both cases, in terms of required SNR threshold for a BER value of 10^{-6} , is around 0.1 dB. However, the behavior of the BER vs SNR curve is not

TABLE V
RELIABILITY/CAPACITY GAIN ANALYSIS
OF THE LL (UNICAST SERVICES)

Metric	NOMA (I)	NOMA (II)
TDL-D 90 ns	1.7	-0.4
TDL-E 90 ns	1.7	-0.6
SNR _{TH} Gain (dB)	1.8	-0.5
TDL-D 360 ns	1.7	-0.4
TDL-E 360 ns	1.8	-0.4
TDL-D 1100 ns	2.0	-0.2
TDL-E 1100 ns	0.2	9.4
Capacity Gain (Mbps)	1	47
Gain in IoT case (Users)	0	5

identical in both cases. While the TDMA case presents a very pronounced decrease, the UL case has a slower decrease. This difference is due to the NOMA configuration. The effective SNR value for the UL is close to 6 dB, due to the IL. This value is very close to the SNR threshold required to decode this configuration in the single layer mode and, in consequence, the UL is not able to offer a fast decrease. Nevertheless, this problem could be solved by increasing the IL value. In that case, the SNR value required to obtain the LL service would be higher.

Regarding the performance in the case of mobile receivers (TDMA (II) and LL), the advantages of the different configurations presented in TABLE IV are confirmed. In TABLE V, an in-depth analysis is carried out in terms of capacity and reliability for the unicast services, which are delivered in the LL in the case of P-NOMA. Each of the metrics presented in TABLE V, demonstrates the gain of P-NOMA over the TDMA configuration. The SNR threshold gain has very little variation over the different channels. As expected, the first P-NOMA configuration presents a reliability gain of 1.7 dB for the same capacity value. The second case offers 9.4 Mbps of capacity gain by assuming a similar reliability performance (0.6 dB of deterioration on the worst case). Overall, these P-NOMA cases present a wide range of transmission configurations.

Last rows of TABLE V also present a capacity gain comparison, but in this case in terms of satisfied users for different potential P-NOMA use cases: IoT services and mobile video delivery. For the first one, the characteristics defined in the Rel-13 (Narrow Band IoT LTE) have been taken into account, where a maximum data rate of 200 kbps per user in downlink channels is allowed [24]. For the second use case, where unicast users will receive HD video content in their mobile or portable devices, a minimum data rate of 2 Mbps has been assumed [25]. From the capacity calculations presented in TABLE V, while TDMA supports 256 unicast

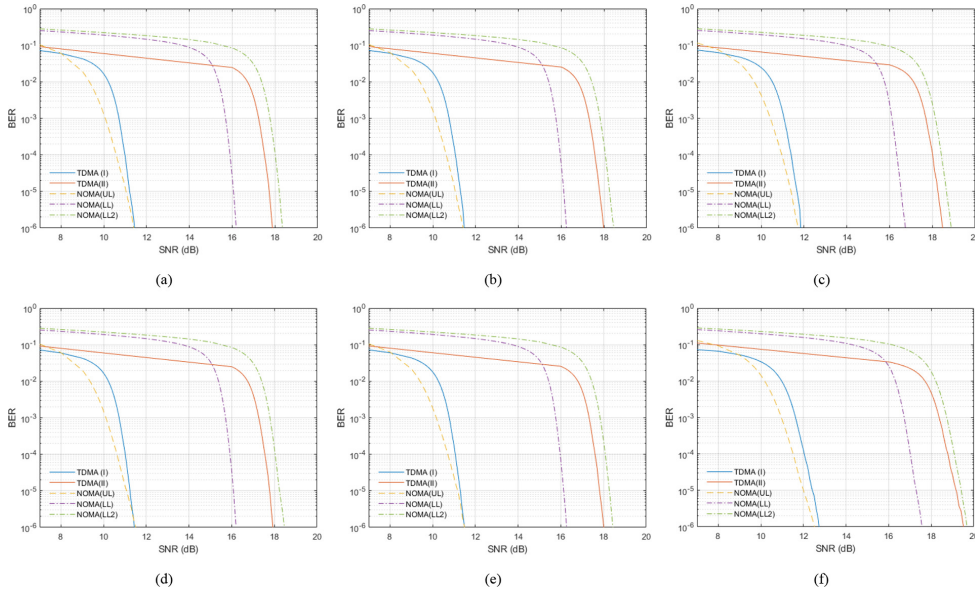


Fig. 5. Performance BER vs. SNR curves for different channel models: (a) TDL-D with 90 ns DDS, (b) TDL-D with 360 ns DDS, (c) TDL-D with 1100 ns DDS, (d) TDL-E with 90 ns DDS, (e) TDL-E with 360 ns DDS, (f) TDL-E with 1100 ns DDS.

users connected in the IoT case and 25 in the mobile video content delivery case, P-NOMA configurations increase considerably the amount of served users with up to 47 IoT devices and 5 mobile video devices.

VI. NETWORK SIMULATION

The objective of this section is to test the performance of the proposed solution including MAC layer techniques and compare the performance with equivalent traditional TDMA solutions.

A. Simulation Methodology

The system evaluation has been carried out in an upgraded OMNeT++ [26]. This network simulation tool is composed of both PHY and MAC layers for each of the implemented transmitters and receivers. On the one hand, the PHY layer module facilitates the selection of the parameters that define the waveform. In addition, the transmission parameters have to be configured (modulation and code rate). PHY performance curves presented in the previous sections are used to estimate the transmission success. For each one of the received packets, the current SNR value of the receiver is used to determine the packet error rate (PER) according to the performance curves. The conversion from BER to PER is carried out following the technique presented in [27]. On the other hand, concerning the MAC layer, HARQ type retransmission schemes are implemented.

Regarding the network architecture and the implemented scenario, the channel model module and the mobility module are the most relevant parts of the simulated model. The

former is in charge of defining the characteristics of the channel model, such as the Doppler frequency, the delay spread value or the implemented channel profile (TDL-D or TDL-E). Indeed, this module is closely related with the user type, since, while the channel for fixed receiver is considered almost constant, the channel affecting the receiver with the highest mobility will show a fastest change. This concept is also taken into account by the mobility model module, which takes care of detailing how the receiver is moving. Different mobility models are available in OMNeT++ for different type of receivers.

B. Network Setup

Three groups of users have been defined: fixed receivers, low-speed pedestrian receivers and car-mounted receivers. The first group of users represents traditional broadcast receivers, based on roof top antenna reception. However, pedestrian and car-mounted receivers will typically request more challenging data applications, e.g., on-demand video content. Therefore, this network architecture emulates a real scenario where a convergence application is required in order to guarantee the correct reception of broadcast and different unicast services.

In each simulation, a total number of 100 devices have been included. Specifically, 75 fixed receivers have been assumed inside each cell, 15 pedestrians and 10 car-mounted user devices. Fixed receivers have a static model, whereas pedestrians have been allocated a concrete walker mobility type referred as Random Way Point (RWP) [28]. In the case of cars, considering the characteristics of city roads, a linear mobility type has been used [29]. Speed is also specified for each

TABLE VI
SIMULATION PARAMETERS

Parameter	Value
Center Frequency	2 GHz
Tx Power	44 dBm
SCS	15 kHz
Distance attenuation	$128.1 + 37.6 \cdot \log(d)$
Type of nodes	Fixed, pedestrians, cars
Speed	Fixed: 0 km/h
	Pedestrians: 3 km/h
	Cars: 30, 50 km/h
Number of Users	Fixed: 75
	Pedestrians: 15
	Cars: 10
Mobility type	Fixed: Static
	Pedestrians: RWP
	Cars: Linear
Inter-Site Distance (ISD)	500 m
Tx configuration (TDMA)	Broadcast: MCS12
	Unicast: MCS19
	Time division: 50%-50%
Tx configuration (NOMA)	Broadcast: MCS5
	Unicast: MCS10, 12
	IL: -6 dB
Desired Delay Spread	90, 360, 1100 ns
Noise Power	-90 dBm
Noise Figure	9 dB
Channel model	TDL-D, TDL-E
Simulated seeds	25
Simulation time	5 min per seed

receiver. Pedestrian receivers walk inside the cell with a mean speed of 3 km/h, and the car receivers vary their speed between 30-50 km/h.

The parameters values are critical when defining the propagation attenuation suffered by the transmitted signal. In this case, all the propagation channels presented in Fig. 5, based on TDL-D and TDL-E, have been considered with specific Doppler frequency values depending on the speed of the receiver.

The rest of the network simulation parameters are gathered in TABLE VI.

C. Results

The evaluation of the proposed NOMA-based 5G model has been based on three KPIs: reliability, latency and throughput. First, to measure the reliability, PER is used as a metric. Second, the user plane latency is evaluated. According to [30], user plane latency is defined as the required time to deliver a data packet between the Next Generation NodeB (gNB) and the user equipment (UE). The user plane latency can be modelled as:

$$T_{UP} = \tau_1 + p(\tau_2 + \tau_3) \quad (6)$$

where, p is the probability of requiring a retransmission, τ_1 is the transmission time, τ_2 is the HARQ request process time and τ_3 is the retransmission time. The complete process to calculate τ_1 , τ_2 and τ_3 is obtained from [31]. The user plane latency is defined by the processing time at the UE ($t_{UE,rx}$). P-NOMA increases latency because the UE processing time will be higher (SIC module). In this case, following the complexity analysis of P-NOMA receivers carried out in [5], it

is assumed that the $t_{UE,rx}$ increase in a two-layer system is 10% in comparison with a LL only case. Therefore, the minimum user plane latency that can be obtained is lower in the TDMA configuration than in the NOMA configuration, 1.785 ms vs. 1.796 ms, respectively. Moreover, the user plane latency deviation is also used in order to measure the latency variation with respect to the achievable minimum latency value. Finally, for the throughput, two metrics are used: normalized data reception index (NDRI) and effective throughput. The NDRI indicates the relation between the amount of information received and the maximum information rate that could be received in the error free case. Moreover, not only error packets reduce the NDRI value, also the delivered retransmissions, since using retransmissions, the overall received capacity is decreased because the same content is repeatedly transmitted. This parameter is measured in percentage data. The following expression has been used to calculate the NDRI:

$$NDRI (\%) = \frac{\text{correct packets}}{\text{correct packets} + \text{retx attempts}} \cdot 100 \quad (7)$$

where, *retx attempts* are the total number of retransmissions that have been carried out for each node. On the other hand, the effective throughput represents the useful received capacity. This parameter also takes into account the number of retransmissions that have been implemented by combing the NDRI with the transmitted capacity:

$$\text{eff. throughput (Mbps)} = \frac{NDRI \cdot \text{tx capacity}}{100} \quad (8)$$

In TABLE VII, a dual comparison of reliability and latency is presented between P-NOMA and TDMA configurations. Fixed receivers (UL) show equal PER values and user plane latency is also the same as no retransmissions are available for those users. User plane latency is the same for TDMA and NOMA cases, since being the service a broadcast type service, there is no uplink to transmit the feedback and, so, retransmissions cannot be implemented. In the case of mobile receivers, in general, the best reliability results are obtained in the NOMA (I) case, which is designed to improve the reliability. PER is reduced by 40% with respect to TDMA. As expected, NOMA (II) presents worse PER values than TDMA configuration. If the reliability is compared between different groups of users, the best results are for fixed receivers because they require lower SNR thresholds. In the case of mobile receivers, car-mounted ones show better behavior for their higher Doppler variation, that will make retransmissions more effective.

In TABLE VII, user plane latency values and deviations are presented. Although NOMA-based receivers have to cope with a latency penalization due to the SIC module, the lowest latency values appear in NOMA (I) because the reliability increase that the configuration offers compensates the latency penalization. In addition, user plane latency values are below 4 ms, which is the user plane latency requirement defined in [31] for eMBB applications. Therefore, all the presented cases meet the latency requirements. Moreover, car receivers have lower user plane latency values than pedestrians. High latency values indicate that more retransmissions

TABLE VII
NETWORK LEVEL RELIABILITY/LATENCY ANALYSIS

User Type	PER			User Plane Latency (ms)			User Plane Latency Deviation (μ s)		
	TDMA	NOMA (I)	NOMA (II)	TDMA	NOMA (I)	NOMA (II)	TDMA	NOMA (I)	NOMA (II)
Fixed (UL)	$3.75 \cdot 10^{-3}$	$3.75 \cdot 10^{-3}$	$3.75 \cdot 10^{-3}$	1.785	1.785	1.785	-	-	-
Pedestrian (LL)	$6.13 \cdot 10^{-2}$	$3.66 \cdot 10^{-2}$	$7.14 \cdot 10^{-2}$	1.908	1.870	1.940	122.519	73.473	143.477
Car (LL)	$2.98 \cdot 10^{-2}$	$1.75 \cdot 10^{-2}$	$3.47 \cdot 10^{-2}$	1.845	1.831	1.866	59.620	35.193	69.737
Total	$1.22 \cdot 10^{-2}$	$7.26 \cdot 10^{-3}$	$1.42 \cdot 10^{-2}$	1.883	1.854	1.910	97.360	58.161	113.981

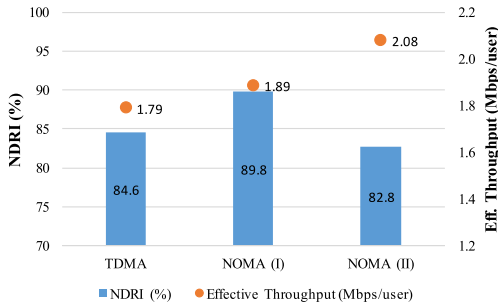


Fig. 6. Network level throughput analysis of the LL (unicast services).

are needed for a proper decoding than in cases with low latency. Therefore, latency results confirm that retransmissions are more effective in the case of cars, while in the case of pedestrians have lower effect. Regarding user plane latency deviation results, NOMA (I) case presents the lowest values, which indicates that the calculated user plane latency is closer to minimum than in any other case. This effect makes NOMA (I) even more interesting as it provides higher degree of determinism.

Fig. 6 shows only mobile receiver throughput (fixed receivers show identical behavior). Looking at the NDRI, the results are equivalent to PER values. NOMA (I) outperforms NOMA (II) and TDMA. If effective throughput is considered, TDMA offers the worst behavior (below 1.8 Mbps/user), while NOMA cases increment the effective throughput when increasing the implemented MCS. The difference between TDMA and the best case (NOMA (II)) is an increment of 14%. These results indicate that the reliability decrease is compensated by transmitting with a higher capacity configuration.

VII. CONCLUSION

This paper proposes a PHY/MAC enabler solution for broadcast and unicast convergence in 5G NR. The solution is based on Power domain Non Orthogonal Multiple Access (P-NOMA). The system configuration parameters have been analyzed, and different configuration options have been discussed. For instance, the IL has been identified as a key configuration parameter for the broadcast/unicast convergence use case since introduces an additional multiplexing variable that provides a wider flexibility range. This flexibility has been used to increase the reliability of the unicast receivers and to deliver higher data rate to the unicast receivers.

A system transceiver prototype has been design and implemented for testing purposes. Two different evaluation

procedures have been developed to obtain the system performance from various perspectives. In the PHY layer analysis, different P-NOMA-based configurations have been defined in order to cover a specific service convergence use case, namely NOMA (I) and NOMA (II). Based on these configurations, possible reliability and/or capacity gains were foreseen first, and then, confirmed by using different AWGN and TDL channel models. In the case of the capacity gain, depending on the configuration used, up to 47 IoT receivers and 5 mobile video receivers could be added to the network. The system level performance has been analyzed using a network simulation environment. Reliability, latency and throughput have been evaluated by using different metrics. Reliability and latency measurements indicate that the most appropriate configuration for those terms for the unicast services is NOMA (I). However, from the capacity perspective, NOMA (II) is the best solution because it offers the highest capacity per user rate. Moreover, HARQ retransmission schemes appear to be more effective when the receivers are moving faster, due to the higher channel response variance. All in all, based on the obtained results, NOMA can be considered as a competitive alternative broadcast/unicast convergence.

There are still some future works on the horizon. On the one hand, concerning the stack protocol, upper layers should be taken into account for future developments. For example, if the network layer is included in addition to the proposed service level convergence, IP-based convergence could also be proposed. In this case, 5G NR could be combined with another technology, such as ATSC 3.0 or DVB-T2. On the other hand, as highlighted in Section V-B, one of the proposed NOMA configurations provides a considerable reliability gain that could be transformed in coverage area improvement. Therefore, similar configurations could be used in rural areas or isolated small areas presenting limitations on the service quality. Finally, new resource management strategies could be combined with this solution. Interesting candidate alternatives are subgrouping techniques based on the architecture proposed in [15].

REFERENCES

- [1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021. Cisco, San Jose, CA, USA, 2017.
- [2] NR; Physical Layer; General Description, Technical Specification Group Services and System Aspects V15.0.0, Standard TS 38.201, Jan. 2018.
- [3] "IMT vision—Framework and overall objectives of the future development of IMT for 2020 and beyond," ITU, Geneva, Switzerland, ITU Recommendation M.2083-0, Sep. 2015.
- [4] L. Zhang *et al.*, "Layered-division-multiplexing: Theory and practice," in *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 216–232, Mar. 2016.
- [5] S. I. Park *et al.*, "Low complexity layered division multiplexing for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 233–243, Mar. 2016.

- [6] L. Fanari *et al.*, "Trends and challenges in broadcast and broadband convergence," in *Proc. IEEE Int. Conf. Elect. Eng. Photon. (EEEPolytech)*, St Petersburg, Russia, 2019, pp. 153–156.
- [7] D. Lecompte and F. Gabin, "Evolved multimedia broadcast/multicast service (eMBMS) in LTE-advanced: Overview and Rel-11 enhancements," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 68–74, Nov. 2012.
- [8] C. Hoymann *et al.*, "LTE release 14 outlook," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 44–49, Jun. 2016.
- [9] A. Ghosh, A. Maeder, M. Baker, and D. Chandramouli, "5G evolution: A view on 5G cellular technology beyond 3GPP release 15," *IEEE Access*, vol. 7, pp. 127639–127651, 2019.
- [10] D. Ratkaj and A. Murphy, Eds., *Definition of Use Cases, Requirements and KPIs, Deliverable D2.1*, 5G-PPP 5G-Xcast project, Oct. 2017.
- [11] J. J. Gimenez *et al.*, "5G new radio for terrestrial broadcast: A forward-looking approach for NR-MBMS," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 356–368, Jun. 2019.
- [12] D. Gomez-Barquero, D. Navratil, S. Appleby, and M. Stagg, "Point-to-multipoint communication enablers for the fifth generation of wireless systems," *IEEE Commun. Stand. Mag.*, vol. 2, no. 1, pp. 53–59, Mar. 2018.
- [13] L. Zhang, Y. Wu, W. Li, K. Salehian, A. Florea, and G. K. Walker, "Improving LTE eMBMS system spectrum efficiency and service quality using channel bonding, non-orthogonal multiplexing and SFN," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Nara, Japan, 2016, pp. 1–8.
- [14] L. Zhang *et al.*, "Layered-division multiplexing: An enabling technology for multicast/broadcast service delivery in 5G," *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 82–90, Mar. 2018.
- [15] J. Montalbán *et al.*, "Multimedia multicast services in 5G networks: Subgrouping and non-orthogonal multiple access techniques," *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 91–95, Mar. 2018.
- [16] J. Zhao, D. Gündüz, O. Simeone, and D. Gómez-Barquero, "Non-orthogonal unicast and broadcast transmission via joint beamforming and LDM in cellular networks," *IEEE Trans. Broadcast.*, submitted for publication.
- [17] L. Zhang *et al.*, "Using non-orthogonal multiplexing in 5G-MBMS to achieve broadband-broadcast convergence with high spectral efficiency," *IEEE Trans. Broadcast.*, vol. 66, no. 2, Jun. 2020.
- [18] E. Iradier, J. Montalbán, D. Romero, Y. Wu, L. Zhang, and W. Li, "NOMA based 5G NR for PTM communications," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, 2019, pp. 1–6.
- [19] L. Michael and D. Gómez-Barquero, "Bit-interleaved coded modulation (BICM) for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 181–188, Mar. 2016.
- [20] S. Ahn, K. Kim, S. Myung, S. Park, and K. Yang, "Comparison of low-density parity-check codes in ATSC 3.0 and 5G standards," *IEEE Trans. Broadcast.*, vol. 65, no. 3, pp. 489–495, Sep. 2019.
- [21] "Study on channel model for frequencies from 0.5 to 100 GHz," 3GPP, Sophia Antipolis, France, Rep. TR 38.901, 2017.
- [22] *Service Requirements for the 5G System; Stage 1, V15.7.0, Release 15, Technical Specification Group Services and System Aspects*, Standard 3GPP TS 22.261, Dec. 2018.
- [23] *NR; Physical Layer Procedures for Data (Release 15), V15.3.0, Technical Specification Group Services and System Aspects*, Standard 3GPP TS 38.214, Sep. 2018.
- [24] S. Persia and L. Rea, "Next generation M2M cellular networks: LTE-MTC and NB-IoT capacity analysis for smart grids applications," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, 2016, pp. 1–6.
- [25] X. Xu, J. Liu, and X. Tao, "Mobile edge computing enhanced adaptive bitrate video delivery with joint cache and radio resource allocation," *IEEE Access*, vol. 5, pp. 16406–16415, 2017.
- [26] A. Varga and R. Hornig, "An overview of the OMNET++ simulation environment," in *Proc. 1st Int. Conf. Simulat. Tools Tech. Commun. Netw. Syst. Workshops (ICST)*, 2008, p. 60.
- [27] Z. Li *et al.*, "A cross-layer design for wireless VoIP: Playout delay constrained ARQ with ARQ aware adaptive playout buffer," in *Advances in Network and Communications Engineering*, 2004, p. 11.
- [28] E. Hytía, H. Koskinen, P. Lassila, and A. Penttinen, "Random waypoint model in wireless networks," in *Networks and Algorithms: Complexity in Physics and Computer Science*, Jun. 2005.
- [29] O. G. Olaleye, A. Ali, D. Perkins, and M. Bayoumi, "Modeling and performance simulation of PULSE and MCMAC protocols in RFID-based IoT network using OMNeT++," in *Proc. IEEE Int. Conf. RFID (RFID)*, Orlando, FL, USA, 2018, pp. 1–5.

[30] "Study on scenarios and requirements for next generation access technologies, v15.0.0," 3GPP, Sophia Antipolis, France, Rep. TR 38.913, Jun. 2018.

[31] E. Garro *et al.*, "5G mixed mode: NR multicast-broadcast services," *IEEE Trans. Broadcast.*, vol. 66, no. 2, Jun. 2020.



Eneko Iradier (Student Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of the Basque Country (UPV/EHU) in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree. Since 2015, he has been part of the TSR Research Group, UPV/EHU. He was with the Communications Systems Group of IK4-Ikerlan as a Researcher from 2017 to 2018. During his doctoral studies, he did an internship at Communications Research Centre Canada, Ottawa. His current research interests include the design and development of new technologies for the physical layer of communication systems and broadcasting in 5G environments.



Jon Montalbán (Member, IEEE) received the M.S. and Ph.D. degrees in telecommunications engineering from the University of the Basque Country, Spain, in 2009 and 2014, respectively. He is part of the Radiocommunications and Signal Processing Research Group, University of the Basque Country, where he is an Assistant Professor involved in several research projects. He has held visiting research appointments with the Communication Research Centre, Canada, and Dublin City University, Ireland. His current research interests are in the area of wireless communications and signal processing for reliable industrial communications. He is the co-recipient of several best paper awards including the Scott Helt Memorial Award to Recognize the Best Paper Published in the IEEE TRANSACTIONS ON BROADCASTING in 2019. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications and currently serves as an Associate Editor for IEEE ACCESS.



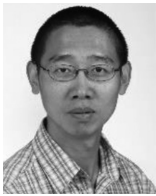
Lorenzo Fanari (Student Member, IEEE) received the B.Sc. degree in electrical and electronic engineering and the M.Sc. degree in telecommunication engineering from the University of Cagliari, Italy, in 2015 and 2018, respectively. He is currently pursuing the Ph.D. degree with the University of the Basque Country, Spain. His research interests include coding theory and wireless communications.



Pablo Angueira (Senior Member, IEEE), received the M.S. and Ph.D. degrees in telecommunication engineering from the University of the Basque Country, Spain, in 1997 and 2002 respectively.

He joined the Communications Engineering Department, University of the Basque Country in 1998, where he is currently a Full Professor. He is part of the staff of the Signal Processing and Radiocommunication Lab (<http://www.ehu.es/tsr>), where he has been involved in research on digital broadcasting (DVB-T, DRM, T-DAB, DVB-T2, DVB-NGH, and ATSC 3.0) for more than 20 years. He has coauthored an extensive list of papers in international peer-reviewed journals, and a large number of conference presentations in digital broadcasting. He has also authored several contributions to the ITU-R working groups WP6 and WP3. His main research interests are network planning and spectrum management applied to digital terrestrial broadcast technologies. He is currently involved in research activities related to broadcasting in a 5G environment.

Prof. Angueira is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, a member of the IEEE BMSB International Steering Committee and a Distinguished Lecturer of the IEEE Broadcast Technology Society. He serves on the Administrative Committee for the IEEE Broadcast Technology Society.



Liang Zhang (Senior Member, IEEE) received the bachelor's degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei, China, in 1996, and the M.S. and Ph.D. degrees from the Department of Electrical and Computer Engineering, University of Ottawa, Ottawa, ON, Canada, in 1998 and 2002, respectively. He is a Senior Research Scientist with the Communications Research Centre Canada, Ottawa. He has been deeply involved in the ATSC 3.0 standardization activities on developing the layered-division-multiplexing technology, mixed fixed and mobile broadcast service delivery, mobile service detection, co-channel interference mitigation, integrated access and backhaul. He is currently working on technologies for the convergence of future TV broadcast and 5G broadband systems. He has more than 70 peer-reviewed Journal and conference publications and received the Multiple Best Paper Awards from IEEE, IBC, and NAB for his work on the Next Generation ATSC 3.0 and the 5G Broadcasting Systems. He is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING and IEEE Broadcast Technology Society Distinguished Lecturer, and the elected member of the IEEE Broadcast Technology Society Administrative Committee.



Yiyang Wu (Fellow, IEEE) received the M.Eng. and Ph.D. degrees in electrical engineering from Carleton University, Ottawa, ON, Canada, in 1986 and 1990, respectively.

He is a Principal Research Scientist with the Communications Research Centre Canada. He is an Adjunct Professor with Carleton University and Western University, Canada. He has more than 400 publications. His research interests include broadband multimedia communications, digital broadcasting, and communication systems engineering. He received many technical awards for his contribution to the research and development of digital broadcasting and broadband multimedia communications. He is a Distinguished Lecturer of the IEEE Broadcast Technology Society, and a member of the ATSC Board of Directors, representing IEEE. He was appointed as a Member of the Order of Canada in 2018. He is a Fellow of the Canadian Academy of Engineering.



Wei Li (Member, IEEE) received the B.E. degree in electrical engineering from Shandong University in 1985, the M.S. degree in electrical engineering from the University of Science and Technology of China, in 1988, and the Ph.D. degree in electrical engineering from the Institut National des Sciences Appliquées of Rennes, France, in 1996. In 2001, he joined Communications Research Centre Canada (CRC), where his major focus is broadband multimedia systems and digital television broadcasting. He is currently a Research Scientist with CRC. He served as the Session Chair for the IEEE International Symposium on Broadband Multimedia Systems and Broadcasting in 2006, 2007, 2015, 2016, and the TPC Chair in 2016. He was the Managing Editor of the IEEE TRANSACTIONS ON BROADCASTING Special Issue on IPTV in Broadcasting Applications in 2009. He also served as a reviewer for several renowned international journals and conferences in the area of broadcasting, multimedia communication, and multimedia processing. He was the BTS IPTV representative at the ITU-T and the Co-Chair of Enhanced TV Planning Team at ATSC. He is the Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING and IEEE ACCESS.

3.1.3 Konferentzia-artikula (K2)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengo da:

- E. Iradier, A. Abuin, L. Fanari, J. Montalban, P. Angueira, L. Zhang, W. Li and Y. Wu, "Broadcast/Unicast Convergence in NOMA-based 5G: a RRM Optimization Algorithm," 2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Paris, France, 2020, pp. 1-6, doi: 10.1109/BMSB49480.2020.9379805.

Hona hemen artikulua honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore-n indexatutako konferentzia
- Saila: Konputazio zientziak eta ingeniari-tza
- SJR faktorea: 0,206

Broadcast/Unicast Convergence in NOMA-based 5G: a RRM Optimization Algorithm

E. Iradier, A. Abuin, L. Fanari, J. Montalban, P. Angueira
Department of Communications Engineering
University of the Basque Country (UPV/EHU)
Plaza Torres Quevedo 1, Bilbao (Spain)
{eneko.iradier, lorenzo.fanari, jon.montalban,
pablo.anguera}@ehu.eus, aritzabuin1@gmail.com

L. Zhang, W. Li, Y. Wu
Communications Research Centre Canada (CRC)
Ottawa, Ontario, K2H 8S2, Canada
{liang.zhang, wei.li, yiyuan.wu}@canada.ca

Abstract— This paper presents an optimization algorithm for resource allocation management in a 5G broadcast/unicast convergence scenario. The convergence of broadcast and unicast services has always been a challenge. In this work, Non-Orthogonal Multiple Access (NOMA) techniques are proposed as the enabler of the broadcast/unicast convergence. Hence, the designed and developed algorithm maximizes the data rate offered for unicast services, while for the broadcast users a predefined minimum percentage of served users and a minimum capacity rate is guaranteed. The algorithm can be executed for NOMA and TDMA. Results indicate that the optimization in the resource allocation level leverages the gain of NOMA techniques in comparison to traditional orthogonal techniques and, therefore, more unicast users could be served by following NOMA solutions. Moreover, in order to mitigate the increment in system complexity due to the introduction of NOMA, a complexity reduction technique has been developed and tested. Results indicate that the performance of the technique varies depending on the target users.

Keywords— 5G, Broadcast, Convergence, LDM, NOMA, NR, P-NOMA, PTM, Resource Allocation, RRM, Unicast.

I. INTRODUCTION

5G is expected to extend the potential application fields of cellular communications to new use cases. According to [1], the application scope has been divided in three different areas: enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC). Each one of those application areas presents different requirements and 5G New Radio (NR) has been designed to cover all of them. For example, while eMBB is oriented to offer high data rates (peak data rate values close to 10-20 Gbps), the URLLC use case is targeting mission-critical communications, where reliability and latency are crucial parameters. Finally, mMTC requires an exponential increase in the device density rate, around 10^6 devices per km^2 .

The already published first 5G NR release (i.e., Rel-15) includes several promising enhancements (e.g., more robust channel coding or a flexible Physical Layer, PHY) [2]. Nevertheless, Point-to-Multipoint (PTM) communications, a mechanism that could enhance the 5G performance, have not been addressed in detail so far and it is expected to be included as part of future releases (Rel-18/19).

In addition to PTM communications, the coexistence of broadcast/multicast services and unicast or Point-to-Point (PTP) services also has to be managed in future 5G releases. Traditionally, Orthogonal Multiple Access (OMA) techniques have been implemented (i.e. Time Division Multiplexing, TDM and Frequency Division Multiplexing, FDM). An example is 4G eMBMS (evolved Multimedia Broadcast Multicast Services), which is based on dividing the resources in the time domain for broadcast/multicast and unicast services [3].

Recent works have demonstrated that the spectral efficiency of NOMA techniques outperform OMA considerably [4]. A good example is the success of Layered Division Multiplexing (LDM), which is a low-complexity power domain NOMA (P-NOMA) solution. LDM was approved in 2016 as part of the ATSC 3.0 PHY layer baseline technology [5].

Following the successful introduction in the ATSC standard, NOMA has also been proposed to be used as a potential enabler for broadcast/multicast and unicast services convergence. In [6], authors propose to use the two-layer architecture provided by NOMA systems to deliver broadcast services in the Upper Layer (UL) and unicast services in the Lower Layer (LL). However, an optimal service configuration in terms of resource allocation and offered capacity values has not been addressed.

The objective of this paper is to design and evaluate a novel algorithm for optimizing the offered capacity and focus on the Radio Resource Management (RRM) on broadcast/unicast service convergence in 5G networks based on P-NOMA. Afterwards, the algorithm is evaluated in terms of capacity and complexity. Finally, some methods are proposed and tested in order to decrease the complexity.

In summary, the technical contributions of this paper include:

- 1) Design and development of a RRM optimization tool for enabling the convergence of broadcast/unicast services in 5G networks using NOMA.
- 2) Capacity performance evaluation of the developed algorithm.
- 3) Complexity evaluation of the developed algorithm and proposals for decreasing complexity.

The rest of the paper is organized as follows. The next section describes the related work published up to now on this topic. Section III is focused on the description of the proposed algorithm. In section IV, a brief description of the simulation methodology and the use case are presented. Then, in section V, the results are presented and analyzed from the capacity and the complexity point of view. Finally, section VI concludes the work.

II. RELATED WORK

In 4G networks, the inclusion of broadcast communications and its co-existence with unicast services was solved by using time and frequency domain multiplexing. Although a first convergence approach was included in 3G systems, the inclusion of eMBMS in 4G, entailed higher and more flexible bit rates, single frequency network (SFN) operations and carrier configuration flexibility [3]. In LTE Release 14, the latest eMBMS version was presented. Release 14 eliminated the restriction of a maximum of 60% of the radio resources allocated for broadcast/multicast [7].

In the case of 5G, a similar roadmap is expected for addressing PTM communications. Some of the most relevant contributions in this area are related to the 5G-Xcast project [8]. This project presented several modifications at different levels of the protocol stack in order to introduce broadcast communications in 5G NR. A good example is found in [9], where a specific approach of the 5G NR PHY to cover the terrestrial broadcast need is presented.

Regarding P-NOMA-based systems (like LDM), although having demonstrated very positive conditions in order to deliver broadcast or multicast contents, they were not included in 4G. However, the integration of NOMA in 5G NR has become again a hot topic inside the debate forums [10]. Previous works have analyzed the possible integration of NOMA techniques in eMBMS environments [10] [11]. Authors in [10] provide a theoretical point of view of the possible use of NOMA as part of 5G capabilities to deliver PTM communications within broadband networks. A second approach [11] demonstrates that NOMA has the potential to become a feasible technique to deliver multicast services in subgroup-oriented communications.

In papers [12]-[14], the use of P-NOMA was analyzed in a 5G-MBMS system for delivering broadcast services with different requirements, and for delivering mixed unicast and broadcast services. Authors provided several results in terms of capacity, where the benefits of using P-NOMA are demonstrated theoretically and carrying out simulations. Broadcast services are configured to be delivered on top of the unicast network with nearly full capacity.

In [15], the first NOMA-based 5G NR PHY layer transceiver was presented. The work addresses simultaneously services convergence and NOMA. Authors provided several results based on specific use cases, where the broadcast/unicast convergence is based on NOMA. Then, in [6], a full PHY/MAC transceiver is presented in order to cope with the service convergence requirements. In this case, network level results demonstrated benefits at different stack levels.

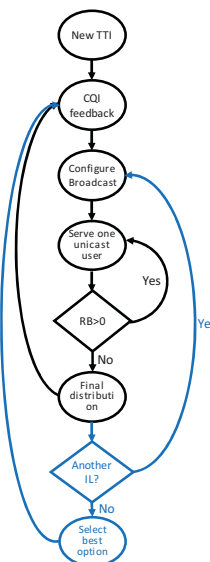


Fig. 1. Proposed algorithm diagram.

Nevertheless, none of those approaches has studied the possibility of optimizing RRM strategy in the broadcast/unicast convergence environment using NOMA.

III. RRM ALGORITHM FOR CONVERGENCE

In Fig. 1, a diagram of the developed algorithm is presented. The algorithm has two different versions, one for TDMA and another one for NOMA. The blocks in black of Fig. 1 are common blocks for both technologies, whereas blue blocks are specific for NOMA. It is important to highlight that the target of this algorithm is the maximization of the capacity offered to the unicast services once a minimum broadcast capacity is maintained. In this case, the unicast services are considered secondary services (or opportunistic services), so the fairness is less of a concern.

The basis of this algorithm is the set of Channel Quality Indicator (CQI) values received from different user equipment (UEs) in the uplink channel. The algorithm processes the received CQIs to optimize the RRM configuration and it is executed in every Transmission Time Interval (TTI). First, CQI_k values from the k UEs that compose the network are received and the number of users requesting each MCS is calculated as $U = \{u_1, u_2, \dots, u_C\}$, where u_c is the number of terminals having a CQI equal to c . Then, the broadcast service is configured according to the percentage of broadcast users which service has to be guaranteed. To do so, the highest MCS that guarantees that the predefined served user percentage constraint being satisfied is selected. If TDMA is selected, a portion of the total amount of Resource Blocks (RB) is reserved for PTM and the rest is for managing the unicast services. However, in the case of NOMA, the whole bandwidth is used for both type of services, broadcast/multicast and unicast.

Once the PTM configuration is applied, the first unicast user is served. As the main objective of this algorithm is to maximize the unicast service throughput, the user requesting the highest Modulation and Coding Schemes (MCS) is served first, since less RBs are needed to achieve the minimum capacity. The MCS selection is carried out according to the Table 5.1.3.1-2 in [16]. When the required RBs for the first user are reserved, it is checked if there are still enough RBs to continue with the next user. If no more RBs are available, the configuration is finished. On the other hand, if there are still free RBs, the next user with the highest MCS request is selected.

If the algorithm is implemented for NOMA, a longer process has to be applied since several Injection Level (IL) values have to be tested. In fact, this algorithm uses a fixed set of IL values composed by values from -20 dB to -0.5 dB in steps of 0.5 dB (i.e., 40 IL values are tested). When the IL is changed, the required SNR to decode any of the NOMA layers is modified and affects the MCS value that is used to serve the users. If high IL values are used, UL presents similar SNR values in comparison with single-layer cases, whereas the SNR for the LL is considerably increased. In that case, it is easier to guarantee the PTM constraint, but fewer unicast users could be served. However, when low IL values are used, the opposite situation occurs: the difference between PTM configurations and single-layer mode is increased and unicast users are easily satisfied. Therefore, after every IL value has been tested, the combination that maximizes the LL throughput while guaranteeing the minimum percentage of PTM users is selected. Clearly, this process implies an increase in the complexity of the RRM algorithm, since more possible configurations have to be considered. This issue is studied more in detail in section V.B and a solution is proposed and evaluated.

IV. SIMULATION FRAMEWORK

A. Simulation methodology

In order to test the algorithms for TDMA and NOMA, a two-step methodology is implemented using two different simulators. In the first step, the CQI requests of each user are gathered per TTI. This task is performed in a network simulator, in OMNeT++, specifically. The inputs to this block are the network parameters and the mobility models. The network parameters define the conditions that affect the path loss calculation, including for example, the propagation channel model, the coverage area or the carrier frequency, among others. On the other hand, the mobility model selection is related to the user type. The speed of the receiver is implemented in this block and it has a close relation with the Doppler frequency that the user has to cope with. Taking into account those parameters, the CQI generator collects the CQI request of each user in each TTI and it is introduced in the algorithm block.

The second step is related with the algorithm itself and it is carried out in Matlab. The first task in this step is to gather all the constraints and conditions that need to be defined before running the algorithm. The minimum throughput constraints for broadcast and unicast are some of the most relevant conditions.

TABLE I
CONFIGURATION PARAMETERS

Parameter	Value
Bandwidth	20 MHz
Carrier Frequency	2 GHz
SCS	15 kHz
Tx Power	44 dBm
Distance attenuation	$128.1 + 37.6 \cdot \log(d)$
ISD	500 m
# of User	100
# of TTI	10000
Minimum PTM data rate	2, 3, 4 Mbps
Minimum Unicast data rate	1, 2, 3, 4 Mbps
Inter-Site Distance	500 m
Channel model	TDL-D, TDL-E
Desired Delay Spread	90, 360, 1100 ns
Noise Power	-90 dBm
Noise Figure	9 dB
Time slot size	1 ms
Mobility type	RWP
User type	Pedestrian, car-mounted
Speed	Pedestrians: 3 km/h Car-mounted: 30 km/h

These values are selected depending on the use case being emulated. The algorithm will use them to calculate how many RBs are required to configure each service type. In the case of broadcast services, the minimum percentage of served users has to be configured as well. Meanwhile, it is necessary to indicate if the algorithm has to evaluate the configuration for TDMA or NOMA. Then, the values generated in the CQI generator step are used as input and the algorithm is executed. Once the algorithm has finished, the data rate offered for the PTM communications, the aggregate data rate (ADR) of the unicast services and the number of served unicast users are presented for their evaluation.

B. Use case configuration

The defined use case assumes that different video qualities and contents are delivered to mobile receivers, while the coexistence of broadcast and unicast transmissions is guaranteed. The configuration parameters are listed in TABLE I.

The main objective of the broadcast content is to deliver a basic common quality service for all the users of the network. In this case, different subsets of the same common use case are evaluated, where values from 2 Mbps to 4 Mbps have been considered in order to guarantee different quality expectations. Then, unicast services are delivered for some of the users of the network to increase their Quality of Service (QoS) by increasing the overall data rate. In this case, a similar range of possible data rates has been assumed (from 1 Mbps to 4 Mbps) in order to enhance the received video quality or to increment the number of simultaneously received video contents.

The major driving factors for use case configuration are the propagation channel model and the user definition. The former is based on [17], which uses two different channel profiles (TDL-D or TDL-E) and three different desired delay spread (DDS) values for each channel model: 90 ns, 360 ns and 1100 ns. Those values have been selected for their alignment with

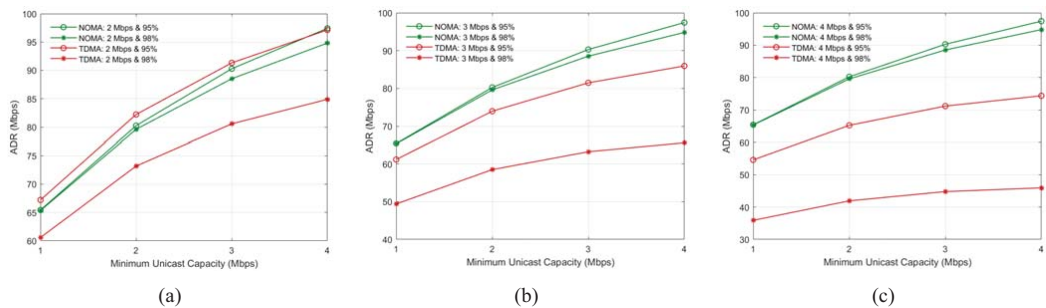


Fig. 2. Unicast ADR results using different PTM minimum capacities: (a) 2 Mbps, (b) 3 Mbps, (c) 4 Mbps.

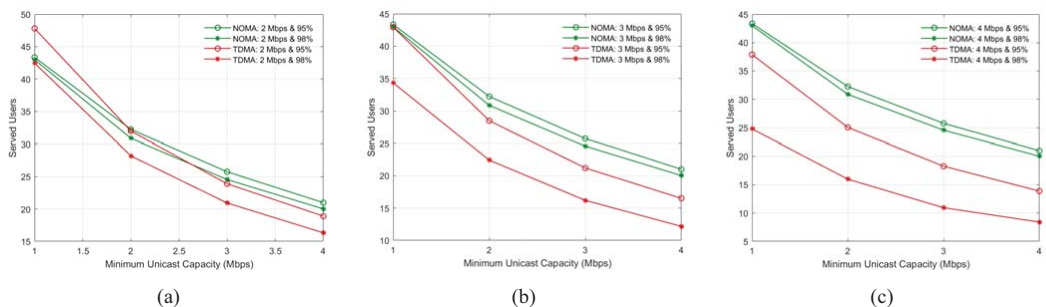


Fig. 3. Number of unicast users served using different PTM minimum capacities: (a) 2 Mbps, (b) 3 Mbps, (c) 4 Mbps.

short-, normal- and long-delay profiles for an urban environment. All the possible DDS and channel profile combination have been simulated jointly in the same cell in order to emulate a realistic scenario where users with different receiving conditions coexist. Actually, the channel model is closely related with the user type, since the channel affecting the receiver with the lowest mobility will vary slowly in comparison with users with higher mobility. This concept is also critical in the mobility model, since it takes care of detailing how the receiver is moving. In this case, the mobility of the receivers is modelled with the Random Way Point (RWP) model [18], which was designed to emulate the mobility of mobile receivers inside the cell. In addition, the speed of the users has been set to 3 km/h for pedestrian receivers and 30 km/h for the car-mounted.

V. RESULTS

Results are divided into two subsections. The first one analyzes capacity results in the case of pedestrian users whereas the second addresses complexity. Finally, a technique for reducing the complexity is proposed and tested with pedestrian and car-mounted users.

A. Capacity

The capacity results of the RRM algorithm are presented in Fig. 2, where ADR values are displayed for different capacity and broadcast served users constraints. First, it should be

highlighted that, for most of the cases NOMA offers better capacity performance than TDMA. The performance gain depends on different constraints. The more challenging the configuration is, the higher the gain that NOMA can achieve. That is why, the highest gains are presented in Fig. 2(c), where at least 4 Mbps have to be dedicated to the PTM service. In particular, for the cases where 3 Mbps and 4 Mbps have to be guaranteed, the capacity offered with NOMA duplicates the capacity of TDMA. However, for the configuration where soft constraints are applied (required PTM capacity < 2 Mbps), TDMA seems to be better option. In addition, the results also show that the TDMA-based algorithm is more sensitive to the constraint of the percentage of broadcast users that have to be served, and NOMA-based algorithm offers similar results for different values. The main reason for this is that when the broadcast users' constraints are more restrictive, less RBs are available for the unicast service configuration and, therefore, some users cannot be served. However, NOMA has always the same number of available RBs for the unicast services.

On the other hand, Fig. 3 shows another perspective for the capacity analysis, the number of unicast users served under the same constraints as in Fig. 2. In general, a similar behavior is observed: NOMA offers better performance and the highest gain appear when the applied constraints are more challenging. In this case, the number of served users decreases while the minimum unicast capacity increases. Fig. 3(a) shows very similar results for both technologies. However, in Fig. 3(c), the

TABLE II
ANALYSIS OF THE PROPOSED COMPLEXITY REDUCING TECHNIQUE

User	Served (%)	σ	MCS' = MCS		MCS' = MCS - 1		MCS' = MCS - 2		MCS' = MCS - 3		MCS' = MCS - 4		MCS' = MCS - 5	
			Gain (Mbps)	Success (%)	Gain (Mbps)	Success (%)	Gain (Mbps)	Success (%)	Gain (Mbps)	Success (%)	Gain (Mbps)	Success (%)	Gain (Mbps)	Success (%)
Pedestrian	95	1/8	8.75	73.37	4.45	81.60	3.11	88.63	-1.36	92.98	-5.59	95.92	-10.05	97.48
		1/16	8.7	72.69	4.41	80.54	3.05	87.64	-1.44	92.23	-5.67	95.15	-10.12	96.94
		1/25	8.82	70.81	4.54	78.42	3.32	85.36	-1.09	90.01	-5.31	93.45	-9.78	95.55
	98	1/40	8.84	68.17	4.56	75.11	3.13	82.50	-1.34	87.70	-5.57	91.37	-10.02	93.67
		1/8	25.32	73.92	21.7	81.63	19.07	88.47	13.94	92.73	9.75	95.63	5.37	97.25
		1/16	25.26	73.33	21.65	80.65	19.01	87.42	13.86	91.99	9.67	94.87	5.29	96.58
Car-mounted	95	1/25	25.29	71.38	21.7	78.52	19.03	85.36	13.92	89.83	9.73	93.20	5.33	95.51
		1/40	25.49	68.68	21.84	75.24	19.18	82.31	14.08	87.40	9.92	91.10	5.53	93.44
		1/8	7.67	65.00	3.34	70.35	2.45	75.66	-1.93	79.89	-6.21	83.86	-10.97	86.94
	98	1/16	7.54	65.48	3.25	70.96	2.37	76.36	-1.98	80.46	-6.28	84.56	-11.04	87.68
		1/25	7.73	65.03	3.43	70.09	2.47	75.67	-1.88	79.99	-6.19	83.92	-10.99	87.29
		1/40	7.65	63.37	3.3	68.96	2.46	74.80	-1.92	79.28	-6.2	82.76	-11	85.74
	98	1/8	23.46	65.35	19.57	70.42	17.85	75.69	12.96	79.90	8.65	83.83	3.95	86.93
		1/16	23.36	65.83	19.51	71.05	17.82	76.41	12.94	80.44	8.63	84.54	3.93	87.70
		1/25	23.59	65.32	19.7	70.16	18	75.71	13.13	79.96	8.82	83.83	4.07	87.15
		1/40	23.59	63.91	19.61	69.02	18.05	74.77	13.24	79.24	8.91	82.68	4.18	85.62

number of unicast users served with NOMA outperforms TDMA considerably. In fact, the maximum gain appears in the last case where 4 Mbps have to be guaranteed for both, PTM and unicast services. In this case, the capacity offered with NOMA is 51.2% and 138% higher than with TDMA for 95% and 98% of broadcast users, respectively.

B. Complexity

When designing a RRM algorithm, complexity is considered one of the main Key Performance Indicators (KPIs). As presented in Fig. 1, TDMA- and NOMA-based algorithms have common steps of the algorithm. However, when NOMA is used, several extra iterations have to be carried out in order to test different IL values. Therefore, the complexity comparison of the NOMA and TDMA can be expressed as:

$$C_{NOMA} = \sum_{\Delta} C_{TDMA} \quad (1)$$

where C_{NOMA} and C_{TDMA} are the computational cost of NOMA and TDMA, respectively. As defined in section III, 40 ILs are tested during the execution of the NOMA-based algorithm and, so, the complexity of NOMA is 40 times higher than in TDMA. However, according to Eq. (1), the complexity of the NOMA-based algorithm will decrease if fewer IL values are tested. Nevertheless, reducing the number of ILs may get the RRM configuration further away from the optimum configurations.

In order to decrease the overall computational cost of the NOMA-based algorithm and targeting a real deployment, the execution frequency of the algorithm will be less than one TTI. Therefore, the complexity of the NOMA-based algorithm varying the execution frequency can be expressed as follows:

$$C_{NOMA} = \sigma \cdot \sum_{\Delta} C_{TDMA} \quad (2)$$

where σ represents the execution frequency, (0,1]. In this case, the complexity increases due to the use of NOMA can be compensated by reducing the execution frequency.

However, the main drawback of this solution is that when the configuration is maintained over several TTIs, as the receivers are moving, they may change their requested CQI and they may not receive correctly the information because they are receiving the data with a MCS higher than the maximum MCS they can decode. That is why, the gain that NOMA has demonstrated in the previous section is invested in reducing the MCS used in the delivery, in order to reduce the mismatch probability between the requested and the received MCS, and therefore, improve the performance of the complexity reduction technique.

This approach has been verified with simulations. The execution frequency (σ) has been varied, as well as the MCS used to serve the users (i.e., MCS'). In order to evaluate the proposed solution, a reduced number of subsets have been evaluated: two different served broadcast users constraints (i.e., 95% and 98%) and 3 Mbps as the minimum capacity constraints for both, unicast and broadcast services. Results are presented in Table II. The performance is analyzed using two metrics: the gain of NOMA (i.e., the difference in offered unicast capacity between NOMA and TDMA) and the receiving success (i.e., the percentage of times that users have received a MCS value below or equal to the maximum MCS that can receive).

Concerning the capacity gain, when 95% of the broadcast users have to be guaranteed, up to two MCS can be decreased without perceivable capacity loss. However, if 98% of the broadcast users are guaranteed, even in the last case where five MCS values are decreased, NOMA outperforms TDMA. This effect is supported by the capacity gain that NOMA offers when the broadcast users' constraint is much increased. Therefore, the complexity reducing technique performs better, when the requirement of the served broadcast users is higher.

On the other hand, regarding the receiving success, better results are obtained for the pedestrian users since they change their requested MCS slower. In fact, the best pedestrian results

are close to 97%, while car-mounted users can guarantee 87% of success. Moreover, the relation between the execution frequency and the success is also different depending on the type of user. While differences around 5% between the highest and the lowest frequencies are observed for pedestrian users, in the case of car-mounted users, almost the same success values are obtained. This result indicates that in the case of car-mounted users, less TTIs should be skipped in order to appreciate an evolution on the success rate.

Finally, the case $\sigma = 1/40$ should be highlighted since it makes TDMA and NOMA complexity equal. In this case, positive results are obtained when the percentage of served broadcast users is high. However, the performance is downgraded when the broadcast users' constraint is reduced. The explanation of this difference is the same as in the previous section, where TDMA was more sensitive to the broadcast users' constraint. Therefore, if the complexity due to the introduction of NOMA techniques in the RRM has to be reduced, a tradeoff has to be assumed between the unicast capacity gain and the performance of the algorithm over users with different mobility types.

VI. CONCLUSIONS

A NOMA-based RRM algorithm has been designed and evaluated to optimize the resource allocation in a broadcast/unicast convergence environment. In addition to the algorithm specifications, capacity and complexity have been analyzed as the main KPIs and a complexity reduction technique has been proposed and verified.

Capacity results indicate that under the optimum resource allocation conditions, NOMA techniques outperform the performance obtained with OMA techniques. In fact, considerable gains in terms of data rate and served users have been presented for the unicast services. On the other hand, the complexity analysis has demonstrated that NOMA-based algorithm increments the computational cost according to the number of IL values tested. In order to reduce the overall computational cost, a complexity reducing technique has been introduced based on the reduction of the execution frequency. The main problem of this solution is the mismatch generated between the requested and the used MCS. Therefore, the capacity gain that NOMA offers has been invested in serving the users with lower MCS values to allow for a margin that increments the success rate. Results indicate that the performance has a considerable influence on the mobility type and the percentage of served broadcast users. In fact, the technique performs better for pedestrian users than for car-mounted users. Moreover, better success results are obtained, when the percentage of served broadcast users is higher, since the capacity gain that NOMA offers w.r.t TDMA is higher.

ACKNOWLEDGMENTS

This work has been partially supported by the Basque Government (project IOTERRAZ under the grant KK-

2019/00046 ELKARTEK 2019, the grant IT1234-19 and the PREDOC grant program PRE 2019_2_0037) and by the Spanish Government (project PHANTOM under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE)).

REFERENCES

- [1] ITU-R Rec. ITU-R M. 2083-0, "IMT Vision — Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Sept. 2015.
- [2] TS 38.201, Tech. Spec. Group Services and System Aspects, "NR; Physical layer; General description," V15.0.0, January 2018.
- [3] D. Lecompte and F. Gabin, "Evolved multimedia broadcast/multicast service (eMBMS) in LTE-advanced: overview and Rel-11 enhancements," in *IEEE Communications Magazine*, vol. 50, no. 11, pp. 68-74, November 2012.
- [4] L. Zhang et al., "Layered-Division-Multiplexing: Theory and Practice," in *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 216-232, March 2016.
- [5] S. Park et al., "Low complexity layered division multiplexing system for ATSC 3.0," in *IEEE Transactions on Broadcasting*, vol. 62, no. 1, Mar. 2016.
- [6] E. Iradier, et al., "Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks," in *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 503-514, June 2020.
- [7] C. Hoymann et al., "LTE release 14 outlook," in *IEEE Communications Magazine*, vol. 54, no. 6, pp. 44-49, June 2016.
- [8] D. Ratkaj and A. Murphy, Eds., "Definition of Use Cases, Requirements and KPIs," Deliverable D2.1, 5G-PPP 5G-Xcast project, Oct. 2017.
- [9] J. J. Gimenez et al., "5G New Radio for Terrestrial Broadcast: A ForwardLooking Approach for NR-MBMS," in *IEEE Transactions on Broadcasting*, vol. 65, no. 2, pp. 356-368, June 2019.
- [10] L. Zhang et al., "Layered-Division Multiplexing: An Enabling Technology for Multicast/Broadcast Service Delivery in 5G," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 82-90, March 2018.
- [11] J. Montalban et al., "Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 91-95, March 2018.
- [12] L. Zhang et al., "Using Layered-Division-Multiplexing to Achieve Enhanced Spectral Efficiency in 5G-MBMS," *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Jeju, Korea (South), 2019, pp. 1-7.
- [13] Y. Xue, A. Alshaily, E. Sousa, W. Li, L. Zhang and Y. Wu, "Using Layered Division Multiplexing for Mixed Unicast-Broadcast Service Delivery in 5G," *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Jeju, Korea (South), 2019, pp. 1-6.
- [14] L. Zhang et al., "Using Non-Orthogonal Multiplexing in 5G-MBMS to Achieve Broadband-Broadcast Convergence with High Spectral Efficiency," in *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 490-502, June 2020.
- [15] E. Iradier, J. Montalban, D. Romero, Y. Wu, L. Zhang and W. Li, "NOMA based 5G NR for PTM Communications," *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Jeju, Korea (South), 2019, pp. 1-6.
- [16] 3GPP TS 38.214 v15.3.0, Tech. Spec. Group Services and System Aspects, "NR; Physical layer procedures for data (Release 15)," Sept. 2018.
- [17] 3GPP TR 38.901. "Study on channel model for frequencies from 0.5 to 100 GHz." 3rd Generation Partnership Project; Technical Specification Group Radio Access Network.
- [18] E. Hyytia, H. Koskinen, P. Lassila, and A. Penttinen, "Random waypoint model in wireless networks," *Networks and Algorithms: Complexity in physics and Computer Science*, June 2005

3.1.4 Aldizkari-artikula (A2)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengo da:

- E. Iradier, M. Fadda, M. Murrone, P. Scopelliti, G. Araniti and J. Montalban, "Non-Orthogonal Multiple Access and Subgrouping for Improved Resource Allocation in Multicast 5G NR," Digital Communications and Networks aldizkarira bidalia.

Hona hemen artikulua honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Telekomunikazioak
- Sailkapena: 12/90 (Q1) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 5,382



Non-Orthogonal Multiple Access and Subgrouping for Improved Resource Allocation in Multicast 5G NR

Eneko Iradier^{a,*}, Mauro Fadda^b, Maurizio Murrone^b, Pasquale Scopelliti^c, Giuseppe Araniti^c, Jon Montalban^a

^aDept. of Communications Engineering, University of the Basque Country, Bilbao, Spain

^bDept. of Electrical and Electronic Engineering - DIEE/UdR CNIT, University of Cagliari, Italy

^cDept. of Information Engineering, Infrastructure, and Sustainable Energy - DIIES, Mediterranean University of Reggio Calabria, Italy

Abstract

The effort of the telecom industry to enhance the Quality of Service (QoS) of the cellular networks has been constant during the last decade. To enable new application scenarios, the last generation of mobile networks (i.e., 5G) is being designed to cope with very stringent constraints in terms of device density, latency, user mobility and peak data rate. Nevertheless, as its predecessor (e.g. LTE), the Radio Resource Management (RRM) only implements Orthogonal Multiple Access (OMA) techniques. On the other hand, within the media vertical, vehicular communications represent a demanding and challenging use case. Up to now, solutions based on multicast transmissions have presented considerable efficiency increments by the successful implementation of subgrouping strategies. These techniques enable a more efficient exploitation of multi-user diversity by splitting users into subgroups and by applying independent and adaptive modulation and coding schemes. However, at the RRM, OMA poses a hard limit in the exploitation of the available resources, especially when users' QoS requests are unbalanced, which is a typical feature of vehicular environments. Under these circumstances, this paper proposes to jointly apply the subgrouping and Non-Orthogonal Multiple Access (NOMA) techniques in 5G for mobile and vehicle receivers. This study shows that NOMA is highly spectrum-efficient and in certain conditions could improve the system throughput performance. In the first part of this paper, an in-depth analysis of the implications of the introduction of NOMA techniques in 5G subgrouping at RRM is carried out, and afterwards, the validation is accomplished by applying the proposed approach to different 5G use cases based on vehicular communications. After a comprehensive analysis of the results, the proposed joint solution improves considerably the data rate offered in each use case.

© 2020 Published by Elsevier Ltd.

KEYWORDS:

5G, ADR, LDM, NOMA, P-NOMA, Resource Allocation, RRM, Subgrouping, Wireless Communications.

1. Introduction

The fifth generation of cellular networks (5G) is being developed to provide groundbreaking connectivity to everyone and everything, everywhere and every-time. 5G networks are expected to cover a wide range of use cases with customized parameters: devices, type of users, requirements and mobility classes. In

2015, the International Telecommunication Union Radiocommunication Sector (ITU-R) issued the International Mobile Telecommunications-2020 (IMT-2020) standard, which are the requirements for 5G networks, devices and services. The IMT-2020 has put forth some requirements for 5G that focus on fulfilling three Key Performance Indicators (KPIs): $> 10\text{Gb/s}$ peak data rates for enhanced Mobile Broadband (eMBB), $> 1\text{M}/\text{km}^2$ connections for massive Machine-Type Communications (mMTC), $< 1\text{ms}$ latency for Ultra-Reliable Low Latency Communications (URLLC) [1].

*Corresponding author Eneko Iradier (email: eneko.iradier@ehu.eus).

The first version of 5G, which is based on the specifications developed by 3GPP in Release 15 (Rel-15), comprises the 5G Core (5GC) and 5G New Radio (NR) with 5G User Equipment (UE) and is currently being deployed commercially throughout the world both at sub-6 GHz and at mmWave frequencies. In Rel-15, there are common elements with 4G Long Term Evolution (LTE) and LTE-A, such as the use of orthogonal frequency division multiplexing (OFDM). The second phase of 5G is being standardized in parallel by 3GPP in the Release 16 (Rel-16). While Rel-15 is focused on eMBB services, Rel-16 includes new features for URLLC, mMTC and Industrial IoT, including Time Sensitive Communication (TSC), Enhanced Location Services (ELS), and support for Non-Public Networks (NPNs). Meanwhile, the feature content of Rel-17 is already underway, targeting specification availability in mid-2021. Rel-17 and beyond is expected to include (but not limited to) enhanced support for wireless and wired convergence, multicast and broadcast architecture, proximity services, multi-access edge computing and network automation [2]. To enable all the potential use cases, high spectral efficiency is one of the main goals to be achieved. As in the previous generation, the radio resource management (RRM) implements orthogonal multiple access (OMA) techniques. Consequently, although 5G has increased the spectral efficiency in comparison with 4G adding flexibility to RRM in the definition of RB allocation, there appears to be still room for improvement.

In multicast transmissions, where users access the same content, RRM is in charge of performing an efficient link adaptation procedure according to the channel conditions experienced by the multicast users. This adaptation has to be accomplished on a per-group basis, taking into account the Channel State Indicator (CSI) of all the users registered to a given multicast service. However, in single rate-transmissions the presence of cell-edge users, which experience poor channel conditions can strongly degrade the Quality of Service (QoS) that the cellular infrastructure could provide. Subgrouping is a solution that has been proposed in literature as an effective technique to overcome those limitations. Based on splitting the multicast users into subgroups and applying subgroup-based adaptive modulation and coding schemes (MCS), it enables more efficient exploitation of multi-user diversity by optimizing opportune cost functions [3]. This solution is very useful for vehicular communications, where the high and rapid variation of the receivers positions lead to unequal reception conditions [4] [5].

In general, vehicular communications imply unbalanced QoS requests from multicast services (e.g., groups with different throughput), and under this situation, OMA could limit the full exploitation of the resources. In such a scenario, Non-Orthogonal Multiple

Access (NOMA) techniques have shown the power to allow increasing spectral efficiency [6]. With respect to OMA, where the available frequency/time resources in the network are orthogonally assigned to the different User Equipments (UEs), in NOMA, UEs share the available resources, both in frequency and time. On the one hand, in OMA at the receiver side, under perfect conditions, the desired data can be unequivocally separated from the rest of the information. On the other hand, in NOMA when decoding the desired content, the rest of the signals are considered an additional source of interference. In [7], NOMA techniques have shown higher efficiencies in comparison with OMA, especially when the throughput rate among different users is asymmetric.

In [8], authors explored the joint use of subgrouping multicast techniques and NOMA in an evolved multimedia broadcast multicast service (eMBMS)-like 5G scenario, where different quality video services were delivered to a group of users interested in the same contents. The potentiality of the proposed approach was preliminary investigated in some envisaged 5G mobility environments and the results in terms of QoS indicators such as maximum throughput (MT) and aggregated data rate (ADR) were promising. The objective of this paper is to go deeper into the study of subgrouping with NOMA techniques in 5G scenarios performing. Therefore, an in-depth analysis of the implications of the introduction of NOMA techniques in 5G subgrouping at the resource allocation level (i.e., RRM) is carried out and the approach is formalized and validated. In particular, although [8] is oriented to 5G networks, it makes use of 4G numerology and the data rate calculations are based on the Shannon's capacity approach. Therefore, this work overcomes those limitations with a novel cost-function design and evaluation.

This study shows how, under opportune conditions, NOMA allows improved performance of subgrouping techniques for efficient resource allocation. In summary, the novel technical contribution of this paper is the comprehensive proposal and evaluation of subgrouping techniques combined with 5G and NOMA which includes:

1. Detection of the penalization of using NOMA for subgrouping and provide a solution.
2. Design of a new evaluation cost function for 5G subgrouping based on NOMA.
3. Comprehensive analysis of the results of different techniques based on variable constraints and vehicular environment network parameters.
4. Identification and theoretical demonstration of the system further evolution.

The rest of the paper is organized as follows. The next section describes the basic principles and related

work published in literature both for subgrouping and NOMA techniques. In section III, the system model and problem formulation for the proposed NOMA-based subgrouping technique are detailed. The simulation framework is presented in section IV, whereas section V is dedicated to the analysis of the results. Future works and system evolution are addressed in section VI. Finally, section VII draws the conclusions.

2. Basic Principles and Related Work

Multicast scheduling can be divided into two types of multicast transmissions: single-rate and multi-rate [9]. In the single-rate case, the base station transmits to all users in each multicast group at the same rate. In multi-rate, instead, the base station transmits to each user at different rates exploiting users' frequency diversity, according to the heterogeneity of the wireless channels. This paper focuses on the latter case. Multi-rate multicast schemes allow each user to receive multimedia traffic based on the capabilities of the UE. In particular, subgrouping is one of the multi-rate techniques that exploits the group-splitting approach. Nevertheless, subgrouping techniques introduce new issues related to subgrouping formation: proper resource allocation, MCS selection, etc. Consequently, many schemes have been proposed by the research community to achieve the optimal solution. This section summarizes the main contributions dividing them between the solutions that do not include NOMA (section 2.2.1) and the ones that take advantage of NOMA (section 2.2.2). Prior to that, NOMA is briefly introduced in section 2.1.

2.1. NOMA

NOMA gathers a wide family of medium access techniques where all users share the same frequency and time resources. As described in [10], non-orthogonal access can be classified into code-domain NOMA [11][12] and power-domain NOMA (P-NOMA) [13][14]. In principle, power domain NOMA presents a better trade off between complexity and capacity [10]. During the rest of the paper, NOMA will refer to power domain NOMA.

P-NOMA is based on the idea of overlapping layers, published by Cover and Bergmans in [15][16] and on a technique referred as Successive Interference Cancellation (SIC). A P-NOMA receiver iteratively demodulates, decodes and cancels successive information layers from the received signal ensemble [17][18].

The capacity gain of NOMA has been demonstrated theoretically [14][19], by simulations [20][21] and in both lab tests and field trials [22][23]. However, this gain depends on the robustness/capacity differences between the services conveyed within the NOMA ensemble. This way, the higher the difference between the NOMA layers (services), the higher the gain. On the contrary, multiplexing services of equal capacity

in NOMA does not provide any overall capacity gain in comparison to OMA structures.

2.2. Multicast subgrouping

Multi-rate multicast transmissions can be divided into two different categories, stream-splitting and group-splitting. Stream-splitting is based on splitting high-rate multimedia contents in multiple substreams of low-rate [24], while group-splitting techniques divide multicast members into different subgroups, each one formed by users experiencing similar channel conditions [25]. The most suitable subgroup configuration is dynamically selected by the eNodeB based on the minimization (or maximization) of a given cost function, which takes into account the users channel quality indicator (CQI) values and the QoS constraints of the multicast session [26].

The subgrouping techniques consist of three stages:

- *CQI collection*: the eNodeB collects the CQI feedbacks from each UE belonging to the multicast group. In particular, each UE estimates its CQI value based on the Signal to Interference and Noise Ratio (SINR) and the target Block Error Rate (BLER). Afterwards, forwards the CQI back (associated to the highest supported MCS) to the eNodeB.
- *Subgroup creation*: the multicast members are split into subgroups. The subgrouping algorithm determines the subgroup configuration that: (i) allows to maximize the system capacity; (ii) guarantees that each served UE can successfully demodulate the received signal; (iii) optimizes a given cost function.
- *Resource allocation*: depending on the configuration defined in the previous step, all the UEs reporting a CQI value equal to the minimum CQI selected for each subgroup will be served with the closest supported MCS.

The optimization problem can be formulated in order to achieve different goals: the maximization of the system throughput, spectral efficiency, energy efficiency, or the minimization of resource utilization. In addition, it worth noticing that it has been mathematically demonstrated that the optimal subgroup configuration when maximizing the ADR has to be searched between a single subgroup and two-subgroups [3].

2.2.1. OMA Techniques

Several subgrouping algorithms and methods can be found in the literature, differing for adopted strategies, optimization functions, or considered physical characteristics. In [27], the authors presented a two-step procedure that merges areas significantly overlapped in space considering similar users' contents, returning multi-content groups that include cells with very

similar content interests, and eventually, broadcasts the most demanded items thus maximizing the system throughput. Then, in [28] it is described an innovative RRM mechanism developed to increase the eMBMS performance by splitting each multicast group into several subgroups according to the users channel quality.

In [29], a multicast subgroup formation method and an Application-Layer Joint Coding (ALJC) technique are combined to improve the performance of multicast satellite transmission through the Land Mobile Satellite (LMS) channel both in terms of throughput and perceived quality of the video streams. On the other hand, in [30] the authors describe a new approach to separate experts in subgroups assigning properly the importance of such subgroup in the resolution of a large-scale group decision making (LS-GDM) problem, in which experts elicit their preferences by fuzzy preference relations (FPRs) and a fuzzy clustering process that computes the subgrouping.

Recently, the work in [31] focuses on the delivery of augmented reality services in urban scenarios considering the 5G NR standard through eMBMS to achieve both higher capacity and lower latency with respect to LTE. In [32], the design of a heuristic algorithm for dynamic eMBMS over single frequency networks (MBSFN) area formation is presented in order to increase the ADR exploiting the multi-rate transmission typical of subgrouping jointly with the scalable video coding (SVC) technique and radio resource allocation for an efficient spectrum utilization in the configured MBSFN areas. Then, in [33], a precoding for max-min fairness (MMF) for multi-group multicasting is designed and evaluated using a common message. This technique turned into a rate-splitting algorithm that combines private and common information in each group. Results provided by the authors highlight that rate-splitting improves the overall performance especially in overloaded systems. Finally, in [34] authors combine game theory developments with multicast grouping algorithms. In fact, it is focused on an indirect reciprocity game framework that tests the device-to-device multicast (D2MD) stimulation problem. In this case, the request nodes (RNs) are grouped and the broadcast content is transmitted by the head node (HN), which will be assigned different reputation values depending on the delivery.

2.2.2. NOMA Techniques

Iradier et al. in [35] analyzed the benefits of LDM technology with subgrouping algorithms into the resource allocation mechanism of LTE-A standard for multicast vehicular communications. In [36], a cooperative transmission scheme is proposed for unicast/multicast transmissions in a downlink Cognitive Radio (CR)-NOMA system, evaluating the performance improvement when the number of secondary users is increased. In [37], it is presented a multi-

ple access method called power domain sparse code multiple access (PSMA), for heterogeneous networks (HetNets), based on the use of codebooks that can be reused more than one time in the coverage area of a base station to improve the system spectral efficiency. The signal model and detection techniques of PSMA together with power domain (PD)-NOMA and sparse code multiple access (SCMA) were investigated for comparison. In [38], a simple user grouping and pairing scheme for NOMA in a downlink visible light communication system is presented. The proposed scheme is a mix of both conventional NOMA and OMA schemes where every two users are paired using NOMA and all pairs are allocated with conventional OMA. The performance of the proposed scheme is compared to conventional OMA in terms of maximum sum rate.

Recently, [39] investigates the possibility of a more spectrum efficient solution in mixed unicast-broadcast service delivery in 5G-MBMS using a power-based non-orthogonal multiplexing (P-NOM) (i.e., LDM) examining the potential capacity gains from using NOMA over OMA in broadband systems (i.e., LTE and 5G-NR). On the other hand, [40] describes a new method to gather users in P-NOMA and NOMA-2000 [41] over different Rayleigh fading channels. NOMA-2000 combines OFDMA signal and multi carrier-code division multiple access (MC-CDMA) signal and MC-CDMA waveform is spread and superposed to OFDMA waveform.

3. System Model and Problem Formulation

The 5G system model is represented by a next generation base station (gNB), providing services to users with different mobility types. In 5G NR systems, the available radio resources are managed on a RB basis. One RB is the smallest frequency resource that can be assigned to a UE; each RB corresponds to 12 consecutive and equally spaced subcarriers. NR supports multiple numerologies with different Subcarrier Spacing (SCS) values, according to the following equation:

$$\Delta f = 15 * 2^\mu \text{ (kHz)}, \quad (1)$$

where μ is the numerology. In this work, $\mu = 0$ is used, which is oriented to eMBB applications. The packet scheduler of the gNB is in charge of properly managing the transmission parameters and the allocation of the RBs according to the CQI feedbacks received from the users. Based on the CQIs, the transmission from the gNB to the users is set with a given MCS. For each MCS, a certain spectral efficiency is achieved in the transmission. The greater is the spectral efficiency, the lower is the number of RBs required to achieve a given data rate.

Concerning spectral efficiency, subgrouping techniques are considered spectrum-efficient techniques, where each subgroup receives a service flow with

a different MCS in an assigned subset of the RBs. While OMA techniques, such as TDMA or FDMA, share the available RF channel resources (i.e., time and frequency) among the subgroups, NOMA-based subgrouping techniques use the transmitted power difference between both layers to multiplex groups.

3.1. SNR adaptation

The Injection Level (IL) is the most relevant parameter of NOMA systems when configuring the overall content distribution. IL defines the power allocation ratio between layers, which indicates how many dB separate the UL from the LL. Therefore, variations in the IL have direct implications on the available SNR values for each layer. This effect is translated in an increase on the required SNR to decode both layers compared with the case where OMA is used. In particular, the SNR required for each layer in linear units can be calculated as:

$$\gamma_i = \frac{1}{\frac{\sigma_i}{\gamma_{SL}} - \sum_{j=i+1}^N \sigma_j}, \quad (2)$$

where, N is the total number of layer (i.e., $N = 2$ in this work), i is the layer identifier (i.e., from 1 to N), γ_{SL} is the equivalent SNR value of the corresponding layer configuration in single-layer mode and σ_i is power allocation ratio for layer i . Following the analysis carried out in [14], σ_i can be calculated as:

$$\sigma_i = \frac{10^{\frac{\Delta_i-1}{10}}}{\sum_{i=1}^N 10^{\frac{\Delta_i-1}{10}}}, \quad (3)$$

where, Δ is the IL expressed in dB.

Then, taking Eq. (2) and Eq. (3), the SNR adaptation for a two-layer system in dB units can be mathematically expressed based on the single-layer case, as defined in [42]. First, the required SNR to decode the UL can be calculated as follows:

$$\gamma_{ul} = \gamma_{sl} + 10 * \log_{10} \left(\frac{1 + 10^{(\Delta/10)}}{1 - 10^{((\gamma_{sl}+\Delta)/10)}} \right), \quad (4)$$

where γ_{ul} and γ_{sl} are the required SNR to decode the UL and the equivalent single-layer signal, respectively. Regarding Eq. (4), the argument of the log function could be negative and, consequently, γ_{ul} would not be defined. To avoid this, a validity range of γ_{ul} is defined with following condition: $\gamma_{sl} + \Delta < 0$. Therefore, it is not possible to apply any Δ value. The election of the IL is conditioned by the required SNR to the decode the signal in single-layer mode. Moreover, the more robust γ_{sl} is (i.e., low SNR values), the greater is the range of applicable Δ values. In addition, as expected, the higher the IL (Δ) value, the more similar are the γ_{ul} and γ_{sl} .

Then, the required SNR to decode the LL can be also calculated based on the single-layer SNR [42]:

$$\gamma_{ll} = \gamma_{sl} - \Delta + 10 \log_{10} \left(1 + 10^{(\Delta/10)} \right), \quad (5)$$

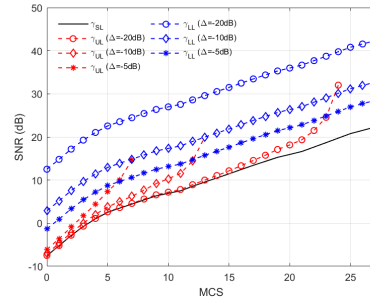


Fig. 1: SNR variation for different MCS cases, layers, and IL values.

where γ_{ll} is the required SNR to decoded the LL.

In Fig. 1, the performance degradation for both layers is shown for different ILs and MCS schemes. The x-axis represents each of the available MCS values in 5G NR according to Table 5.1.3.1-2 in [43], while in the y-axis the required SNR (in dB) value to decode each MCS is shown. The solid black line represents the single-layer case. Regarding UL, it is probed that the higher the IL is, the lower is the difference between single-layer and NOMA case. On the other hand, LL presents the opposite behavior.

3.2. User reorganization

The users' feedback is delivered by the CQI values, which are related to the maximum MCS that the UE is able to decode correctly. The CQI calculation is performed assuming a single-layer transmission mode, and therefore, before applying any NOMA-based subgrouping technique, the SNR adaptation formulas (4) and (5) have to be implemented. However, for the gNB, the CQI feedback represents a range of possible SNR. In fact, when a user requests a specific MCS, the current SNR value that the user has is inside a range of possible SNR values limited by the boundary SNR values of the MCSs. The following expression represents the SNR range: $\gamma_N \leq \gamma_{real} < \gamma_{N+1}$, where N is the MCS requested by the user and γ_N and γ_{N+1} are the minimum required SNR values to decode the MCS N and $N + 1$, respectively. Consequently, when the gNB receives the CQI, it cannot guess the exact SNR value that the user has in order to carry out the SNR adaptation in the NOMA case. This uncertainty could downgrade the delivered capacity or, in the worst case, let some users out of the service because they have a real SNR value below the assumed value. The uncertainty cannot be completely solved, but in this paper it is proposed to reorganize the CQIs of users in the subgrouping process to minimize its effect. In particular, three different user reorganization algorithms have been developed and included in the SNR adaptation process together with the cost function evaluation.

3.2.1. Worst case election

The first technique assumes that, within the range of possible SNR values that a user can have before requesting a specific MCS values, the user will have the worst possible. This implies that the capacity that NOMA is going to offer after the subgrouping configuration will be downgraded since not all users will require such strict SNR values within the range of possible SNRs. On the other hand, none of the users will receive a signal with a required SNR higher than their current SNR. In short, it is not a realistic assumption and it is very pessimistic.

3.2.2. Uniform SNR distribution

This algorithm takes for granted that users requesting the same MCS value will have different SNR values. Consequently, the UEs are uniformly distributed among the possible SNR values. It represents a more realistic case and the final capacity will not be severely downgraded. However, it might be the case where a particular user is assigned to a group with higher requirements than its actual SNR value.

3.2.3. Uniform distance distribution

Another alternative is to assume that the position of the users within the coverage ring related to a particular MCS value are uniformly distributed. As in the previous case, it represents a more realistic scenario and, on the other hand, the throughput will not be downgraded. Nevertheless, a particular mismatch could also happen between the real and the assumed SNR after the reorganization.

3.3. Cost function

First, a TDMA-based cost function has been developed as shown in Algorithm 1. The input is the CQI feedback (i.e., CQI_k) perceived by each k^{th} UE connected to the gNB in each Transmission Time Interval (TTI). Using these collected feedback values, the CQI distribution vector $U = \{u_1, u_2, \dots, u_c\}$ is generated (line 8), where u_c indicates the number of UEs perceiving a CQI equal to c , c varying from 0 to 27, according to Table 5.1.3.1-2 in [43].

Afterwards, the MCS values duple $s_m = [s_{1m}, s_{2m}]$, which provides the maximum cost function value has to be found. The first item, s_{1m} , represents the MCS value assigned to the first group and s_{2m} represents the minimum supported MCS for the second group. Users with lower channel gain are grouped into the s_{1m} subgroup, whereas users under better channel condition are served through higher MCS in the s_{2m} subgroup. For each duple $[s_{1m}, s_{2m}]$, the cost function is iteratively calculated varying the number of resources N_{rb} assigned to each subgroup. Eventually, the configuration that achieves the maximum ADR is the selected (lines 10-14). The ADR is computed as the sum of the data rates of users belonging to both subgroups, according to the MCS values ($[s_{1m}, s_{2m}]$) of the selected

Algorithm 1 TDMA algorithm.

- 1: **Define:** N_{rb} . The number of RB available in the channel bandwidth;
 - 2: **Define:** $m = 1, \dots, M$. Set of possible configurations of couples of MCS values;
 - 3: **Let** t_m be the rate achieved using a single resource block using a MCS value = m ;
 - 4: **Define:** $r = 1, \dots, N_{rb}$. Set of possible RB assigned to the first subgroup;
 - 5:
 - 6: **INITIALIZATION:** Request the previously obtained CQI_k values for each user;
 - 7:
 - 8: **Create the CQI distribution vector:**

$$U = \{u_1, u_2, \dots, u_c\};$$
 - 9: **Find the best configuration of MCS levels couple and RBs distribution:**
 - 10: **for** $m \leq M$ **do**
 - 11: **for** $r \leq N_{rb}$ **do**
 - 12: $ADR_{r,m} = r * s_{1m} * t_{1m} + (N_{rb} - r) * s_{2m} * t_{2m}$
 - 13: **end for**
 - 14: **end for**
 - 15:
 - 16: $[s_{1r,m}, s_{2r,m}] = \text{Arg max } \{ADR_{r,m}\};$
-

configuration and to the number of RB assigned to each subgroup:

$$ADR = r * u_{1m} * t_{1m} + (N_{rb} - r) * u_{2m} * t_{2m}, \quad (6)$$

where r is the amount of RBs assigned to first subgroup, t_{1m} is the rate achieved with a single resource unit (i.e., 1 RB) by users belonging the first subgroup (s_{1m}), t_{2m} is the rate achieved with a single resource unit by users belonging the second subgroup (s_{2m}).

In [8], although NOMA was evaluated, the cost function was based on Shannon capacity formula. Therefore, in this work, several modifications have been included to take into account the numerology that imposes 5G NR [43]. The cost function implemented for carrying out 5G subgrouping using NOMA is presented in Algorithm 2. In this case, it is possible to choose one of the three available user reorganization techniques described in subsection 3.2 (i.e., NOMA (I), NOMA (II), and NOMA (III), respectively) as an additional input. The first step, line 7, is the same as in Algorithm 1. In the second step (line 8), the minimum SNR (γ_{min}) required to decode the MCS related to each CQI in single-layer mode is evaluated:

$$\gamma_{min} = (2^{eff} - 1) * (-\log(5 * BER)/1.5). \quad (7)$$

The formula is obtained from [44] and according to the authors, the Bit Error Rate (BER) has been set to $5 \cdot 10^{-5}$. Then, a loop is defined for different Δ values (line 10), evaluating the rest of the steps iteratively. In order to set the range of possible injection levels (Δ), the same range as in ATSC 3.0 has been used [45]. It is

Algorithm 2 NOMA algorithm.

- 1: **Define:** N_{rb} . The number of RB available in the channel bandwidth;
- 2: **Define:** $m = 1, \dots, M$. Set of possible configurations;
- 3: **Define:** $l = \Delta_1, \dots, \Delta_L$. Set of possible injection levels;
- 4:
- 5: **INITIALIZATION:** The CQI requested by each user has been previously obtained as CQI_k ;
- 6:
- 7: **Create the CQI distribution vector:**

$$U = \{u_1, u_2, \dots, u_C\};$$
- 8: **Calculate the SNR related to each CQI according to:**

$$\gamma_{min} = (2^{eff} - 1) * (-\log(5 * BER)/1.5);$$
- 9: **Evaluate different IL values:**
- 10: **for** $l \leq \Delta_L$ **do**
- 11: **Apply SNR adaptation and calculate** γ_{min-UL} **and** γ_{min-LL}
- 12: **Apply the corresponding SNR reorganization technique:**

$$U_{UL} = \text{Reorganize}(U, \gamma_{min-UL});$$

$$U_{LL} = \text{Reorganize}(U, \gamma_{min-LL});$$
- 13: **Obtain the configuration that maximizes the ADR for different Δ and different configurations:**
- 14: **for** $m \leq M$ **do**

$$ADR_{m,l} = N_{rb} * (s_{1,m} * U_{UL,m} + s_{2,m} * U_{LL,m});$$
- 15: **end for**
- 16: **end for**
- 17: $[s_{1,m}, s_{2,m}] = \text{Arg max } \{ADR_{m,l}\};$

composed by 31 values, where steps of 1 dB are used for Δ between -25 dB and -5 dB and steps of 0.5 dB between -5 dB and 0 dB.

The first step inside the loop is to calculate the minimum SNR required to decode the MCS related to each CQI in the two-layer mode (γ_{min-UL} and γ_{min-LL}). This evaluation process is carried out according to the formulas (4) and (5). Once the limit SNR values are calculated, one of the three available user reorganization techniques described before is applied and new CQI distribution vectors are obtained, for UL and LL, respectively (line 12). The results obtained for each of the reorganization techniques will be compared in Section 5. Then, similar to the second step in Algorithm 1, different configurations are searched to find the one with the highest ADR. As shown in line 14, in this case the whole bandwidth is used for configuring both groups, that is, each of the NOMA layers uses N_{rb} resources. This search is iteratively carried out by varying Δ . The combination of ($s_m = [s_{1,m}, s_{2,m}]$) and Δ finally provides the output of the algorithm.

3.3.1. Complexity

In addition to the functionality of each cost function, the computational complexity is also considered another KPI in RRM algorithms. In this case, the number of operations that defines the computational burden of each cost function is based on a double iterative process, which carries out different operations inside the loop. In fact, NOMA has to perform more operations as shown in lines 12 and 13 of Algorithm 2. Regarding the iterative processes, while in the TDMA-based cost function the parameters that define the iterative process are m and r , in the case of NOMA are l and m . This means that the overall complexity of both solutions depends firstly on the number of possible solutions and, then, TDMA is conditioned by the amount of RBs that can be shared (i.e., r) and NOMA by the amount of IL values (i.e., l). Therefore, the number of iterations in TDMA is $N_{rb} * M$, while in NOMA is $L * M$. In this particular case, the NOMA-based cost function has less iterations since the number of IL values is lower than the number of available RBs for typical 10 MHz and 20 MHz channels (31 vs. 50 and 31 vs. 100, respectively). Consequently, the NOMA-based approach presents better computational complexity characteristics than TDMA, especially when the channel bandwidth increases.

4. Simulation Environment

In this section, the simulation methodology and the use cases defined to evaluate the proposed algorithms are shortly described.

4.1. Methodology

The simulation framework is based on a dual simulation tool. On the one hand, a network level simulator is used to emulate a specific network configuration and to obtain the periodical CQI reports from the users. And on the other hand, a mathematical simulator is used to implement the algorithms presented in section 3.3.

Regarding the network level simulator, OMNeT++ has been used [46]. Using this simulation tool, each user in the cell periodically sends its CQI to the gNB and these feedback values are saved and used as input for the second part of the simulation framework. In particular, the CQI election of the users is conditioned by the propagation channel, which is based on [47], and by the mobility model that each user follows.

Finally, concerning the mathematical simulation tool, Matlab has been used. In this part, the subgrouping algorithms described in section 3.3 are performed. Two different subgrouping algorithms have been evaluated, based on TDMA and NOMA, Algorithm 1 and Algorithm 2, respectively. Both use the CQI values obtained from the mobility model generator module as input to perform their assessment.

Table 1: Simulation parameters

Parameter	Value
Center Frequency	2 GHz
Tx Power	44 dBm
Distance attenuation	$128.1 + 37.6 \cdot \log(d)$
Type of nodes	Pedestrians, car-mounted
Speed	Pedestrians: 3 km/h Car-mounted: 30-50 km/h
Number of Receivers	100
Mobility type	RWP
ISD	500 m
Delay Spread	90, 360, 1100 ns
Noise Power	-90 dBm
Noise Figure	9 dB
Time slot size	1 ms
Evaluated time slots	10000
SCS	15 kHz
Bandwidth	10, 20 MHz
Injection levels	As defined for ATSC 3.0 [45]
Channel model	TDL-D, TDL-E

4.2. Scenario

An urban mobile network environment has been emulated as close as possible to the real environments. Two types of users have been defined: low-speed pedestrian and car-mounted receivers. Due to the characteristics of urban environments and the user types, the Random Way Point (RWP) mobility model [48] has been implemented. In addition, the speed is also specified for each receiver type. In this case, pedestrian receivers walk inside the cell with a mean speed of 3 km/h and the car receivers randomly vary their speed between 30 and 50 km/h.

Taking into account that mobile receivers will use small size screens to display the video content, the minimum data rate for delivering High Definition (HD) or Ultra High Definition (UHD) content has been established between 1 and 4 Mbps [49]. The minimum data rate that has to be guaranteed for both groups of users will be discussed and analyzed in detail in the following section.

The CQI feedback is sent from each user to the gNB in each time slot. According to the implemented numerology (i.e., $\mu = 0$, SCS = 15 kHz), this TTI is equal to 1 ms. The rest of the network simulation parameters are summarized in Table 1.

5. Results

In this section, the most relevant results are presented and analyzed considering two approaches. In the first case, neither capacity constraint, nor user constraints have been applied. In the other cases, minimum capacity constraints and minimum percentages of served users have been defined and applied.

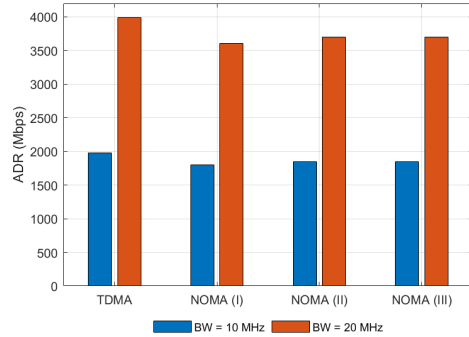


Fig. 2: Case 0 - ADR results.

5.1. Case 0: Without constraints

Firstly, in Fig. 2 ADR results are presented for car-mounted users moving with a speed between 30 km/h and 50 km/h. The vertical and the x-axis represent the ADR in Mbps and the multiplexing configurations, respectively. In the NOMA case, the three reorganization techniques presented in section 3.2 are depicted. The main conclusion is that similar results are obtained for both multiplexing technologies (i.e., TDMA and NOMA). Considering the 10 MHz channel bandwidth, results are almost equal, while in the case of 20 MHz, TDMA offers slightly better results. This is due to the limitation of the IL values, which maximum is set to -25 dB. If more separation between layers is applied, the difference between TDMA and NOMA is reduced.

However, when the mean data rate delivered by each group and the percentage of users served by each group are analyzed, as shown in Table 2, both TDMA and NOMA present unfair configurations. On the one hand, in TDMA, the algorithm assigns almost all the resources to one group and the other group receives just one RB. With this configuration the group with the lowest data rate offers 90 kbps, which is not enough to guarantee mobile video reception. On the other hand, in the NOMA-based solutions, the drawback is that due to the SNR penalization suffered in both layers, the algorithms present groups where users are not served (i.e., 38.03-38.56%) because of the high SNR requirements.

Simulations have also been carried out for pedestrian users moving with a mean speed of 3 km/h. The results have not been included in this work because, without any constraint, are almost the same showed in Fig. 2 and Table 2.

5.2. Case 1: Capacity and users constraints

In order to guarantee that each group is fairly configured, a minimum capacity and percentage of served users constraints have been defined. For the capacity constraint, four different values have been defined:

Table 2: Served users and offered capacity analysis in Case 0 results

BW	Metric	TDMA		NOMA (I)		NOMA (II)		NOMA (III)	
		G1	G2	G1	G2	G1	G2	G1	G2
10 MHz	Served users (%)	42.50	57.50	0.4	61.51	0.97	61.00	0.2	61.24
	Non-served users (%)	0		38.09		38.03		38.56	
	Data rate (Mbps)	0.08	34.88	7.83	29.59	7.75	30.66	7.86	30.42
20 MHz	Served users (%)	42.48	57.52	0.4	61.51	0.97	61.00	0.2	61.24
	Non-served users (%)	0		38.09		38.03		38.56	
	Data rate (Mbps)	0.08	70.45	15.66	59.17	15.50	61.32	15.72	60.84

1, 2, 3, and 4 Mbps. This constraint has to be guaranteed simultaneously in each group and it has been selected according to the potential users requirements described in section 4.2. If it is not possible to guarantee the constraint, a single-group configuration is applied. For the users percentage constraint, two different restrictions have been applied: 90% and 95%. This constraint represents the total number of users of the configuration, which is calculated by adding the number of users served in each group.

Fig. 3 depicts the results obtained for pedestrian and car-mounted users using 10 MHz (light blue box) and 20 MHz (light orange box) channel bandwidths. Overall, NOMA-based configurations outperform the results obtained with TDMA. Nonetheless, the difference between the technologies varies considerably depending on the constraints. If the minimum capacity constraint is used (i.e., 1 Mbps), similar results are obtained for both technologies with the 10 MHz bandwidth (i.e., results inside light blue boxes), while TDMA outperforms NOMA in the 20 MHz case (i.e., results inside light orange boxes). However, when the highest constraint is used (i.e., 4 Mbps), the gain of NOMA is maximized for all the cases. The maximum gain appears for the 10 MHz bandwidth, where the ADR that NOMA offers is more than two times the ADR of TDMA configuration: 120.7% for pedestrian users and 155.9% for car-mounted users. The main reason for these results is that NOMA performs better than TDMA when the most challenging conditions are requested due to the unbalance between the received CQIs.

Also, the influence of the channel bandwidth can be analyzed thanks to graphical results summarized in Fig. 3. On the one hand, more extreme values are obtained using a 10 MHz bandwidth and the minimum and the maximum gains of NOMA are maximized in this case. Consequently, the gain that NOMA offers in relative terms is maximized. On the other hand, in the 20 MHz bandwidth case, results are more linear compared with the ones obtained for the 10 MHz case. In fact, results are constant for all the capacity constraints in the NOMA cases. This effect is due to the use of NOMA, which allows each group to exploit the 100% of the bandwidth resources. Therefore, if the transmission is delivered using the lowest MCS (i.e., QPSK 120/1024 and 0.2344 bps/Hz), the obtained ca-

capacity is 4.22 Mbps, which is always above the capacity constraints.

Table 3 shows the data rate that is offered by each group for some cases shown in Fig. 3. As in the case of the ADR, the gain obtained by using NOMA is maximized when the most challenging conditions are imposed. In fact, for the 10 MHz channel, the high capacity group (i.e., G2) offers up to three times the capacity offered in TDMA when 4 Mbps are required, while in the case of 1 Mbps, the gain is considerably reduced. On the other hand, the user percentage constraint does not affect TDMA cases since as neither SNR adaptation, nor user reorganization are required, all the user in the network are always served. However, in NOMA cases when the percentage of users is increased, the obtained ADR is reduced. Although the reduction varies depending on the case, it is always below 18%. The worst situation is obtained in the case of 10 MHz bandwidth with the 4 Mbps capacity constraint, where a deterioration of 17.3% is obtained for pedestrians and 15.8% for car-mounted users when increasing from 90% to 95% served users.

Finally, the difference between the proposed NOMA-based algorithms in terms of ADR should be remarked. The algorithm that assumes uniform SNR distribution (i.e., NOMA (II)) is the one that performs better. However, the difference between the NOMA-based solutions is around 10% with respect to the worst case election algorithm (i.e., NOMA (I)) and around 5% with respect to the uniform distance distribution algorithm (i.e., NOMA (III)). These results indicate that a trade-off has to be assumed between the maximum capacity that is going to be offered and the potential mismatch between the requested and the offered MCS.

6. Future work and system evolution

Although NOMA-based subgrouping techniques have better performance in comparison with TDMA-based techniques, they cannot be considered the optimum solution. In 3(a) and Fig. 3(b), the ADR results are almost constant for different capacity constraints. That is why, a solution based on the combination of NOMA and T/FDMA techniques could achieve an optimum exploitation of the resource management. In

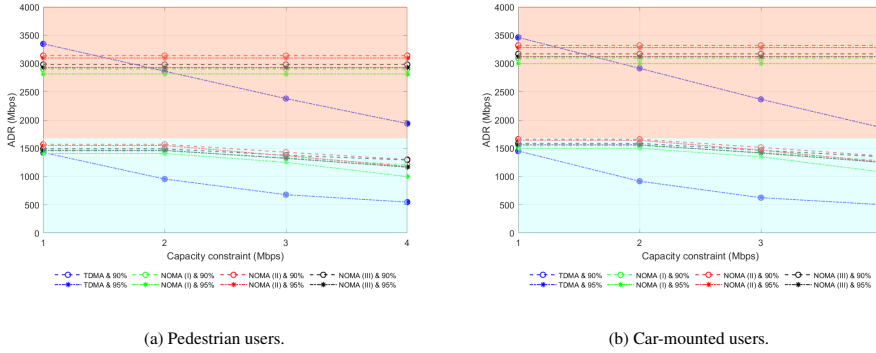


Fig. 3: ADR results with minimum capacity and served users constraints for different configurations and mobility types.

Table 3: Example of mean data rate offered to each group for car-mounted users and 95% of served broadcast users

	TDMA		NOMA (I)		NOMA (II)		NOMA (III)	
	G1	G2	G1	G2	G1	G2	G1	G2
10 MHz & 1 Mbps	1.0	25.6	2.1	32.8	2.1	32.4	2.1	32.9
10 MHz & 4 Mbps	4.0	5.6	4.2	9.9	4.2	18.9	4.2	20.0
20 MHz & 1 Mbps	1.0	61.0	4.2	65.51	4.2	64.8	4.2	65.8
20 MHz & 4 Mbps	4.1	32.4	4.2	65.5	4.2	64.8	4.2	65.8

this section, a theoretical approach is provided in order to prove that future T/FDMA+NOMA solutions are viable.

Taking into account the algorithm developed for NOMA (see Algorithm 2), the resource allocation management implemented by NOMA techniques implies that the 100% of the channel bandwidth resources are used to simultaneously deliver the content for both multicast groups. As the low capacity group (i.e., UL - Group 1) uses all the available resources, the minimum capacity offered can be calculated as follows:

$$C_{G1} = N_{RB} \cdot BW_{RB} \cdot e_{ff} \quad (8)$$

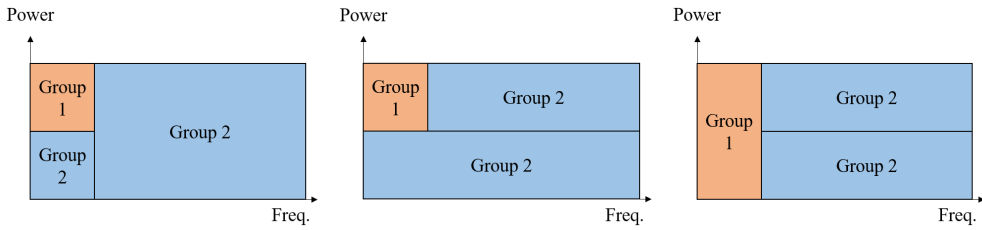
where, BW_{RB} is the bandwidth size of a unique RB, in this case 180 kHz (i.e., 12 subcarriers with 15 kHz of subcarrier spacing). Assuming that the lowest MCS value is used for the transmission, the channel bandwidth defines the offered capacity. In the case of 10 MHz bandwidth (i.e., 50 RB), the minimum capacity that is going to be offered using NOMA is 2.11 Mbps, while if a 20 MHz bandwidth (i.e., 100 RB) is used, 4.22 Mbps can be offered. Therefore, in the case of NOMA the capacity constraint is not as relevant as in the case of T/FDMA, the capacity is always above the constraints established.

The solution is to offer a combination of both techniques. In Fig. 4, different alternatives for the combined NOMA + T/FDMA resource allocation are presented. Fig. 4(c) provides the most robust Group 1 services among the three options since single layer mode is used. On the other hand, Fig. 4(b) presents the

highest spectral efficiency improvement since all the channel resources are shared in both layers. However, this alternative is the less robust solution since all the services are affected by the injection level. Then, Fig. 4(a) presents an intermediate solution, where services of the Group 2 are provided in single-layer mode and in the LL.

Doubtlessly, the RRM algorithm for each solution is different. For example, concerning 4(a), first, some channel resources are assigned to the NOMA based part to configure the low capacity group (i.e., Group 1) and will vary depending on the capacity constraint that is applied. Then, the high capacity group (i.e., Group 2) is configured in the NOMA part with the same number of RBs as in the case of Group 1. Finally, the remaining RBs are used to maximize the capacity offered to Group 2 and the transmission is carried out in single-layer mode. It is important to highlight that the portion of data delivered in the single-layer mode has to be configured to be decoded with the same SNR value (or lower) than the LL. It is quite evident that these approaches provide a more accurate RRM, in exchange for an increase in the complexity of the algorithm since more SNR and capacity values will have to be handled and, therefore, the possible solutions will considerably increase. That is why, this paper includes a theoretical analysis of the potential capacity gain that combined NOMA+T/FDMA solutions will have in future implementations.

The preliminary evaluation results are summarized in Table 4. For the calculations, a 20 MHz (i.e., 100



(a) Group 1 in UL and Group 2 in LL and single-layer (b) Group 1 in UL and Group 2 in UL and LL (c) Group 1 in single-layer and Group 2 in UL and LL

Fig. 4: Different resource allocation representations of the TDMA+NOMA solution.

Table 4: Analysis of the theoretical offered capacity using a combined T/FDMA + NOMA approach

	NOMA-only		T/FDMA+NOMA (1 Mbps)		T/FDMA+NOMA (2 Mbps)		T/FDMA+NOMA (3 Mbps)		T/FDMA+NOMA (4 Mbps)	
	# RB	Mbps	# RB	Mbps	# RB	Mbps	# RB	Mbps	# RB	Mbps
G1 - UL MCS 0	100	4.22	24	1.01	48	2.03	72	3.04	95	4.01
G2 - LL MCS 4	100	21.16	24	5.08	48	10.16	72	15.24	95	20.11
G2 - SL MCS 10	0	0	76	35.16	52	24.06	28	12.95	5	2.31
Total G2	100	21.16	100	40.24	100	34.22	100	28.19	100	22.42

RB) channel bandwidth is assumed following the approach presented in 4(a). The reference NOMA configuration is a configuration obtained from the simulations carried out in section 5.2, where Group 1 uses the lowest MCS, Group 2 is delivered with MCS 4 and the IL is -5 dB. Then, four different approaches of the T/FDMA+NOMA solutions are presented for four different capacity constraints: 1, 2, 3, and 4 Mbps. The gain obtained in the capacity of Group 2 should be highlighted. In fact, the lower the capacity constraint, the higher the gain obtained with the combined solution. For a minimum capacity equal to 1 Mbps, the overall capacity offered for Group 2 is around the double of the capacity offered in the NOMA-only mode.

7. Conclusions

A NOMA-based 5G NR subgrouping techniques have been designed and tested. Besides the design and implementation of the required algorithms, the impact on the SNR deterioration due to the use of NOMA has been detected and opportune solutions based on user reorganization techniques have been proposed.

First, it has to be highlighted that if no constraint is applied, both proposals, NOMA and TDMA, present unfair configurations from the served users or minimum capacity point of view, respectively. Then, once the fairness constraints are applied, NOMA appears as a better candidate. In general, NOMA outperforms TDMA in terms of ADR in almost all the cases. It has

been demonstrated that the variables affecting the configuration (capacity and users constraints and channel bandwidth) are critical to determine the gain of NOMA. In fact, the gain of NOMA is maximized in the most challenging situations. Regarding the proposed algorithms, NOMA (II) presents the highest ADR values, although the difference among the algorithms is not critical (between 5%-10% of deterioration). Finally, both multiplexing technologies, NOMA and TDMA, have been considered as suboptimal solutions since results could be considerably improved combining TDMA and NOMA solutions in the same subgrouping algorithm. Based on the results obtained in section 6, the novel T/FDMA+NOMA solution will considerably outperform any of the proposed solutions that use a single multiplexing technology.

There are still some future works on the horizon. On the one hand, the performance of these subgrouping algorithms should be analyzed from the network layer perspective by using a network simulator. This approach could lead to a novel PHY/MAC analysis of the subgrouping techniques. In addition to the KPIs used in this work (ADR or data rate per group), KPIs related with the PHY and the MAC layers could be used, such as latency, effective throughput or Packet Error Rate (PER). On the other hand, the combination of TDMA and NOMA solutions should be analyzed more in detail and the influence of the rest of the affecting parameters should be studied. Then a simulation platform that integrates a new cost function for

TDMA+NOMA case should be developed.

Acknowledgements

This work was supported by the Italian Ministry of University and Research (MIUR), within the Smart Cities framework, Project Cagliari2020 ID: PON04a2_00381, by the Basque Government (the grant IT1234-19 and the PREDOC grant program PRE_2019_2_0037) and by the Spanish Government (project PHANTOM under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE)).

References

- [1] 3GPP “ETSI TR 121 915 V15.0.0 – Digital cellular telecommunications system (Phase 2+) (GSM); Universal Mobile Telecommunications System (UMTS); LTE; 5G; Release description; Release 15” Oct. 2019.
URL https://www.etsi.org/deliver/etsi_tr/121900_121999/121915/15.00.00_60/tr_121915v150000p.pdf
- [2] A. Gosh, A. Maeder, M. Baker, D. Chandramouli, 5G evolution: View on 5G cellular technology beyond 3GPP release 15, *IEEE Access* 7 (2019) 127639–127651. doi:10.1109/ACCESS.2019.2939938.
- [3] G. Araniti, M. Condoluci, M. Cotronei, A. Iera, A. Molinaro, A Solution to the Multicast Subgroup Formation Problem in LTE Systems, *IEEE Wireless Commun. Letters* 4 (2) (2015) 149–152. doi:10.1109/ACCESS.2019.2939938.
- [4] L. Militano, D. Niyato, M. Condoluci, G. Araniti, A. Iera, G. M. Bisci, Radio resource management for group-oriented services in lte-a, *IEEE Transactions on Vehicular Technology* 64 (8) (2015) 3725–3739.
- [5] M. Condoluci, G. Araniti, A. Molinaro, A. Iera, Multicast resource allocation enhanced by channel state feedbacks for multiple scalable video coding streams in lte networks, *IEEE Transactions on Vehicular Technology* 65 (5) (2016) 2907–2921.
- [6] E. Iradier, J. Montalban, L. Fanari, P. Angueira, L. Zhang, Y. Wu, W. Li, Using noma for enabling broadcast/unicast convergence in 5g networks, *IEEE Transactions on Broadcasting* 66 (2) (2020) 503–514.
- [7] S. M. R. Islam, N. Avazov, O. A. Dobre, K.-s. Kwak, Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges, *IEEE Commun. Surveys & Tutorials* 19 (2) (2017) 721–742. doi:10.1109/COMST.2016.2621116.
- [8] J. Montalban, P. Scopelliti, M. Fadda, E. Iradier, C. Desogus, P. Angueira, M. Murrioni, G. Araniti, Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques, *IEEE Communications Magazine* 56 (3) (2018) 91–95. doi:10.1109/MCOM.2018.1700660.
- [9] R. O. Afolabi, A. Dadlani, K. Kim, Multicast Scheduling and Resource Allocation Algorithms for OFDMA-Based Systems: A Survey, *IEEE Communications Surveys Tutorials* 15 (1) (2013) 240–254. doi:10.1109/SURV.2012.013012.00074.
- [10] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, L. Hanzo, Nonorthogonal Multiple Access for 5G and Beyond, *Proceedings of the IEEE* 105 (12) (2017) 2347–2381.
- [11] R. Hoshyari, F. P. Wathan, R. Tafazolli, Novel low-density signature for synchronous CDMA systems over AWGN channel, *IEEE Transactions on Signal Processing* 56 (4) (2008) 1616–1626.
- [12] F. Brannstrom, T. M. Aulin, L. K. Rasmussen, Iterative detectors for trellis-code multiple-access, *IEEE Transactions on Communications* 50 (9) (2002) 1478–1485.
- [13] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, I. Chih-Lin, H. V. Poor, Application of non-orthogonal multiple access in LTE and 5G networks, *IEEE Communications Magazine* 55 (2) (2017) 185–191.
- [14] L. Zhang, W. Li, Y. Wu, S.-I. Wang, Xianbin Park, H. M. Kim, J.-Y. Lee, P. Angueira, J. Montalban, Layered-Division-Multiplexing: Theory and Practice, *IEEE Transactions on Broadcasting* 62 (1) (2016) 110964–110971. doi:10.1109/TBC.2015.2505408.
- [15] T. Cover, Broadcast channels, *IEEE Transactions on Information Theory* 18 (1) (1972) 2–14.
- [16] P. Bergmans, T. Cover, Cooperative broadcasting, *IEEE Transactions on Information Theory* 20 (3) (1974) 317–324.
- [17] R. Zhang, L. Hanzo, A unified treatment of superposition coding aided communications: Theory and practice, *IEEE communications surveys & tutorials* 13 (3) (2010) 503–520.
- [18] P. Gandotra, R. K. Jha, S. Jain, Green NOMA with multiple interference cancellation (MIC) using sector-based resource allocation, *IEEE Transactions on Network and Service Management* 15 (3) (2018) 1006–1017.
- [19] D. Gómez-Barquero, O. Simeone, LDM versus FDM/TDM for unequal error protection in terrestrial broadcasting systems: An information-theoretic view, *IEEE Transactions on Broadcasting* 61 (4) (2015) 571–579.
- [20] J. Montalban, I. Angelo, C. Regueiro, Y. Wu, L. Zhang, S.-I. Park, J.-Y. Lee, H. M. Kim, M. Velez, P. Angueira, Performance study of layered division multiplexing based on SDR platform, *IEEE Transactions on Broadcasting* 61 (3) (2015) 436–444.
- [21] C. Regueiro, J. Montalban, J. Barrueco, M. Velez, P. Angueira, Y. Wu, L. Zhang, S.-I. Park, J.-Y. Lee, H. M. Kim, LDM core services performance in ATSC 3.0, *IEEE Transactions on Broadcasting* 62 (1) (2016) 244–252.
- [22] S.-I. Park, J.-Y. Lee, B.-M. Lim, Y. Kim, S. Kwon, H. M. Kim, J. Kim, Field test results of layered division multiplexing for the next generation DTV system, *IEEE Transactions on Broadcasting* 63 (1) (2016) 260–266.
- [23] S.-I. Park, J.-Y. Lee, B.-M. Lim, S. Kwon, J.-H. Seo, H. M. Kim, N. Hur, J. Kim, Field comparison tests of LDM and TDM in ATSC 3.0, *IEEE Transactions on Broadcasting* 64 (3) (2017) 637–647.
- [24] C. Suh, J. Mo, Resource allocation for multicast services in multicarrier wireless communications, *IEEE Transactions on Wireless Communications* 7 (1) (2008) 27–31. doi:10.1109/TWC.2008.060467.
- [25] E. Araniti, M. Condoluci, L. Militano, A. Iera, Adaptive Resource Allocation to Multicast Services in LTE Systems, *IEEE Transactions on Broadcasting* 59 (4) (2013) 658–664. doi:10.1109/TBC.2013.2271387.
- [26] G. Araniti, V. Scordamaglia, M. Condoluci, A. Molinaro, A. Iera, Efficient Frequency Domain Packet scheduler for Point-to-Multipoint transmissions in LTE networks, in: 2012 IEEE International Conference on Communications (ICC), 2012, pp. 4405–4409. doi:10.1109/ICC.2012.6364383.
- [27] C. Casetti, C.-F. Chiasserini, F. Malandrino, C. Borgiattino, Area formation and content assignment for LTE broadcasting, *Computer Networks* 126 (2017) 174–186. doi:10.1016/j.comnet.2017.07.006.
- [28] M. Alghareem, M. H. Omar, R. F. Rahmat, R. Budiarto, A Low-Complexity Subgroup Formation with QoS-Aware for Enhancing Multicast Services in LTE Networks, in: 2nd International Conference on Computing and Applied Informatics 2017. doi:10.1088/1742-6596/978/1/012094.
- [29] G. Araniti, I. Bisio, M. De Sanctis, F. Rinaldi, A. Sciarone, Joint Coding and Multicast Subgrouping Over Satellite-eMBMS Networks, *IEEE Journal on Selected Areas and Communications* 36 (5) (2018) 1004–1016. doi:10.1109/JSAC.2018.2832818.
- [30] A. Labella, R. M. Rodriguez, G. De Tre, L. Martinez, A Cohesion Measure for Improving the Weighting of Experts’ subgroups in Large-scale Group Decision Making Clustering Methods, in: 2019 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), New Orleans, LA, USA, 23–26 June

2019. doi:10.1109/FUZZ-IEEE.2019.8858858.
- [31] N. Benenati, C. Desogus, P. Scopelliti, E. Iradier, J. Montalbán, M. Murrioni, G. Araniti, P. Angueira, M. Fadda, Group-oriented broadcasting of augmented reality services over 5g new radio, in: 2019 IEEE Broadcast Symposium (BTS), 2019, pp. 1–7. doi:10.1109/BTS45698.2019.8975412.
- [32] G. Araniti, F. Rinaldi, P. Scopelliti, A. Molinaro, A. Iera, A Dynamic MBSFN Area Formation Algorithm for Multicast Service Delivery in 5G NR Networks, IEEE Transactions on Wireless Communications 19 (2) (2020) 808–821. doi:10.1109/TWC.2019.2948846.
- [33] A. Z. Yalcin, M. Yuksel, B. Clerckx, Rate splitting for multi-group multicasting with a common message, IEEE Transactions on Vehicular Technology (2020) 1–1.
- [34] B. Zhang, Y. Chen, J. Yu, Z. Han, An indirect-reciprocity-based incentive framework for multimedia service through device-to-device multicast, IEEE Transactions on Vehicular Technology 68 (11) (2019) 10969–10980.
- [35] E. Iradier, J. Montalbán, G. Araniti, M. Fadda, M. Murrioni, Adaptive resource allocation in lte vehicular services using ldm, in: 2016 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), 2016, pp. 1–6. doi:10.1109/BMSB.2016.7521985.
- [36] L. Lv, J. Chen, Q. Ni, Cooperative Non-Orthogonal Multiple Access in Cognitive Radio, IEEE Communications Letters 20 (10) (2016) 2059–2062. doi:10.1109/LCOMM.2016.2596763.
- [37] M. Moltafet, N. Mokari, M. R. Javan, H. Saeedi, H. Pishro-Nik, A New Multiple Access Technique for 5G: Power Domain Sparse Code Multiple Access (PSMA), IEEE Access 6 (2017) 747–759. doi:10.1109/ACCESS.2017.2775338.
- [38] E. M. Almohimmah, M. T. Alreshedi, A. F. Abas, J. Elmighani, A Simple User Grouping and Pairing Scheme for Non-Orthogonal Multiple Access in VLC System, in: 20th International Conference on Transparent Optical Networks (ICTON), 1-5 July 2018, Bucharest, Romania. doi:10.1109/ICTON.2018.8473907.
- [39] Y. Xue, A. Alsohaily, E. Sousa, W. Li, L. Zhang, Y. Wu, Using layered division multiplexing for mixed unicast-broadcast service delivery in 5g, in: 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), 2019, pp. 1–6. doi:10.1109/BMSB47279.2019.8971940.
- [40] Y. Yin, Y. Peng, M. Liu, J. Yang, G. Gui, Dynamic User Grouping-Based NOMA Over Rayleigh Fading Channels, IEEE Access 7 (2019) 110964–110971. doi:10.1109/ACCESS.2019.2934111.
- [41] H. Sari, A. Maatouk, E. Caliskan, M. Assaad, M. Koca, G. Gui, On the foundation of NOMA and its application to 5G cellular networks, in: 2018 IEEE Wireless Communications and Networking Conference (WCNC), 15-18 April 2018, Barcelona, Spain. doi:10.1109/WCNC.2018.8377142.
- [42] J. Montalbán, L. Zhang, U. Gil, Y. Wu, I. Angulo, K. Salehian, S.-I. Park, B. Rong, W. Li, H. M. Kim, et al., Cloud transmission: System performance and application scenarios, IEEE Transactions on Broadcasting 60 (2) (2014) 170–184.
- [43] 3GPP TS 38.214 v15.3.0, Tech. Spec. Group Services and System Aspects, NR; Physical layer procedures for data (Release 15), Tech. rep. (Sept. 2018).
- [44] A. J. Goldsmith, S.-G. Chua, Variable-rate variable-power MQAM for fading channels, IEEE transactions on communications 45 (10) (1997) 1218–1230.
- [45] Advanced Television Systems Committee and others, ATSC Standard: Physical Layer Protocol (A/322). Doc. A/322: 2106, Washington, DC, USA.
- [46] A. Varga, R. Hornig, An overview of the OMNeT++ simulation environment, in: Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2008, p. 60.
- [47] 3GPP TR 38.901, Radio Access Network Working Group and others, Study on channel model for frequencies from 0.5 to 100 ghz (release 15), Tech. rep. (2018).
- [48] E. Hyttiä, H. Koskinen, P. E. Lassila, A. Penttinen, J. T. Virtamo, J. Roszik, Random waypoint model in wireless networks, 2005.
- [49] X. Xu, J. Liu, X. Tao, Mobile edge computing enhanced adaptive bitrate video delivery with joint cache and radio resource allocation, IEEE Access 5 (2017) 16406–16415.

3.1.5 Aldizkari-artikulua (A3)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- E. Iradier, A. Abuin, R. Cabrera, I. Bilbao, J. Montalban and P. Angueira, "Advanced NOMA-based RRM Schemes for 5G mmWave Bands," IEEE Transactions on Broadcasting aldizkarira bidalia.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 69/266 (Q2) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,419

Advanced NOMA-based RRM Schemes for 5G mmWave Bands

Eneko Iradier, *Graduate Student Member, IEEE*, Aritz Abuin, *Graduate Student Member, IEEE*, Rufino Cabrera, *Graduate Student Member, IEEE*, Iñigo Bilbao, *Graduate Student Member, IEEE*, Jon Montalban, *Senior Member, IEEE*, Pablo Angueira, *Senior Member, IEEE*,

Abstract—A relevant solution for the high demand for new multimedia applications and services is millimeter frequency bands (mmWave) in 5G. However, in order to face the technological challenges of the present and those that will appear in the short-term future, it is necessary to improve the spectral efficiency of 5G systems. In particular, the Radio Resource Management (RRM) module is considered an essential aspect. However, resource allocation techniques that combine orthogonal multiplexing (OMA) schemes, such as Time Division Multiplexing (TDM), with Non-Orthogonal Multiple Access (NOMA) techniques have not been studied in depth. Therefore, this article designs and evaluates different RRM models that combine TDM with NOMA for innovative applications in the 5G mmWave bands. To this end, the advantages and challenges associated with mmWave bands and potential future applications are introduced. To test the RRM models, an innovative use case has been designed based on the on-demand distribution of multimedia content in high-density environments, such as museum halls. The models have been evaluated in terms of throughput, capacity, and availability. According to the results, the combined RRM techniques offer up to 50% more capacity than the single multiplexing technology models and can provide video-on-demand service to practically the entire cell.

Index Terms—5G, AR, broadcast, LDM, millimeter bands, mmWaves, NOMA, personalization, resource allocation, RRM, unicast.

I. INTRODUCTION

Serving the constant evolution of multimedia services requested by users has become one of the most relevant challenges of today's wireless communication networks. The emergence of new applications such as Augmented Reality (AR) and Virtual Reality (VR) or the increase in the definition of video services (4k/8k) has caused the data rate required by the end-user to grow exponentially during the last years. In fact, according to recent studies, around three-fourths of the data consumed in the world is expected to be video by the end of 2021 [1].

5G is expected to be the technology that leads the implementation of the most challenging and demanded use cases. In fact, the Radiocommunication Sector of the International Telecommunication Union (ITU-R) has divided the entire application frame into three use case families: enhanced Mobile

Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC) [2]. Each of these three families has very different requirements. For example, eMBB, which is based on traditional multimedia delivery, requires around 10 Gbps of peak data rate values for the uplink and around 20 Gbps for the downlink. Moreover, high mobility rates have to be also supported (up to 500 km/h). Then, URLLC is oriented to mission-critical applications, where reliability (loss rates below 10^{-9}) and end-to-end latency (up to 1 ms) are the most critical Key Performance Indicators (KPI). Finally, mMTC is focused on covering extremely crowded networks, such as Internet of Things (IoT) or sensor networks. In this case, density rates above 10^6 devices per km^2 have to be guaranteed.

To serve such a broad set of applications, the first version of 5G New Radio (NR) [3], presents an increase in the robustness of the services thanks to the Low-Density Parity-Check (LDPC) codes and better use of radio resources. Additionally, 5G implements a flexible physical layer (PHY) in which the parameters can be configured to suit the latency or capacity needs required by the application. Another of the most representative novelties is the switch to the millimeter-wave (mmWave) frequency bands, where bandwidths of hundreds of MHz can be allocated [4].

In addition to going up in frequency, an improvement in the spectral efficiency of 5G can facilitate the implementation of the most demanding use cases. In particular, Non-Orthogonal Multiple Access (NOMA) techniques have presented a very promising performance vs. complexity trade-off during the last years. In fact, an excellent example of the success of NOMA happened in 2016, when a low-complexity solution (Layered Division Multiplexing, LDM) was accepted to be part of the PHY of the latest Advanced Television Systems Committee (ATSC) standard [5]. Moreover, NOMA solutions have also been proposed to be combined with broadband standards such as 4G [6] or 5G [7], based on the capacity advantage that they offered in comparison with traditional Time or Frequency Domain Multiplexing (TDM/FDM) solutions. However, recent studies have discovered that although the Radio Resource Management obtained with NOMA techniques outperforms TDM or FDM, it is still a non-optimal solution [8]. As opposed to TDM/FDM, the main reason for this is that NOMA solutions are short of flexibility when Resource Blocks are allocated. Therefore, the combination of NOMA and TDM/FDM techniques in the same RRM scheme could optimize the resource allocation issue.

Eneko Iradier, Aritz Abuin, Rufino Cabrera, Iñigo Bilbao, Jon Montalban, and Pablo Angueira are with the Department of Communications Engineering, University of the Basque Country (UPV/EHU), Torres Quevedo 1, 48012 Bilbao, Spain (email: eneko.iradier@ehu.eus, aabuin003@ikasle.ehu.eus, rufinoydel.cabrera@ehu.eus, inigo.bilbao@ehu.eus, jon.montalban@ehu.eus, pablo.anguera@ehu.eus).

This paper aims to analyze the possible RRM schemes that combine NOMA and TDM techniques for 5G mmWave bands. The advantages and disadvantages of the implementation of 5G in mmWave bands have to be analyzed. Then, different NOMA+TDM RRM schemes have to be designed and evaluated under novel use cases oriented to potential applications for mmWave bands. In summary, the technical contributions of this paper include:

- 1) Analysis of the challenges and benefits of using mmWave bands in 5G, as well as a description of the potential applications.
- 2) Design of different RRM schemes that combine NOMA and TDM multiplexing.
- 3) Evaluation of the proposed RRM schemes under an innovative use case for future mmWave band applications.

The rest of the paper is organized as follows. The next section describes the related works published up to now on this topic. Section III is focused on the overview of the impact of the mmWave bands in 5G and the potential future applications. In Section IV, the proposed NOMA+TDM RRM schemes are designed and detailed. Then, in Section V the use case is introduced, and Section VI presents the results obtained with the RRM schemes in the proposed use case based on different evaluation metrics. Finally, Section VII contains the conclusions.

II. RRM IN MMWAVE BANDS: RELATED WORK

Increasing the center frequency of the services enables the use of bandwidths greater than previous standards. Therefore, the design of RRM algorithms that efficiently manage a large number of radio resources is crucial [9]. This section presents some of the most relevant studies in the literature concerning RRM in the mmWave bands.

One of the main concerns of the applications carried out in the mmWave bands is to coordinate the access of different service requests. For example, in [10], the resource allocation strategy is evaluated in mixed multicast/unicast traffic environments using queuing theory. To do so, a mathematical model is developed to optimize the 5G parameters. The authors define a set of conditions that considerably affect the unicast RRM management, such as significant unicast requests or high spatial arrival intensity. Another alternative to handle users/services with different characteristics is to use heterogeneous networks. In particular, in [11], the authors study the resource allocation in multiple heterogeneous networks in the mmWave bands, where each band has specific propagation conditions. Two different access techniques are proposed: the single-band access scheme and the multi-band access scheme. The first approach is based on the time fraction allocation, whereas the second is based on a Markov model framework. Results indicate that multi-band schemes outperform single-band solutions, especially when the network is in light load mode.

In addition to the networks implemented in the mmWave bands, many applications will continue to be based on sub-6 GHz networks, mainly due to the lower path losses. Therefore, the correct coordination of both frequency bands and managing the resources dedicated to each of the bands is another of

the RRM challenges. This issue is discussed in [12], where resource allocation techniques are studied inside a broader framework that also considers relay address, beam selection, and interference coordination. In this case, the sub-6 GHz band and the mmWave band are used simultaneously with different objectives. While the first is used for control and reliable communications, the latter is used for high throughput applications. The authors evaluate the coordinated management of the multi-parameter framework in both frequency bands at the same time. Then, in [13], the authors propose a diverse network, where sub-6 GHz macrocells and mmWave bands small cells co-exist. The study targets to obtain an energy-efficient RRM algorithm using uplink NOMA in ultradense Internet of Thing (UD-IoT) environments. Results indicate that the proposed algorithm outperforms the existing works.

Then, another relevant issue of the mmWave bands is the correct implementation and optimum use of the backhaul signal. Concerning this challenge, in [14], the Radio Access (RA) and the backhaul (BH) are implemented in the same mmWave band, and so, both services are unified in the same network. The authors present three dynamic RRM algorithms to manage the resource allocation between RA and BH for several pico stations together. Algorithms are oriented to enhance the network capacity and guarantee fairness among stations. The results indicate that the network capacity could be increased up to 35% when the proposed dynamic algorithms are used.

Finally, the RRM algorithms oriented to mmWave bands have to be adapted to novel use cases, such as Unmanned Aerial Vehicle (UAV) applications. For example, in [15], the RRM performance is evaluated in downlink-UAV networks that implement antenna sectoring approaches. In this case, the goal is to maximize the network capacity while ensuring a minimum data rate to each user and limiting the transmission power.

Although several works have been presented in the literature about different RRM algorithms in mmWave bands, the potential gain obtained by combining non-orthogonal techniques with orthogonal techniques, such as TDM or FDM, has not been studied. This work studies and evaluates different combined NOMA+TDM RRM alternatives for a use case applicable in networks based on mmWave bands.

III. 5G IN MMWAVE BANDS

This section discusses the main implications of the implementation of 5G in mmWave bands. The propagation channel conditions and the potential gains are presented and the description of the potential applications.

A. Configuration

The 5G configuration is different in the millimeter frequency band and the sub-6GHz band. Therefore, this subsection analyzes the main differences and their impact on the system.

Firstly, it should be noted that although technically the radioelectric spectrum defined as millimeter frequency band is between 30 GHz and 300 GHz (wavelengths between 10 mm and one mm), in the 5G ecosystem, mmWave bands are

TABLE I: Influence of the numerology value over different waveform parameters

μ	SCS (kHz)	#Slot/Subframe	Slot (ms)	OFDM Symbol (μ s)	CP (μ s)	Total Length (μ s)	RB_{MAX}	BW_{MAX} (MHz)
0	15	1	1	66.67	4.69	71.36	275	49.5
1	30	2	0.5	33.33	2.34	35.67	275	99
2	60	4	0.25	16.67	1.17	17.84	275	198
3	120	8	0.125	8.33	0.57	8.90	275	396
4	240	16	0.0625	4.17	0.29	4.46	138	397.44

understood as the frequencies above 6 GHz [16]. In particular, the frequency band reserved for mmWaves is defined as the Frequency Range 2 (FR2) and is comprised between 24.25 GHz and 52.6 GHz. According to the latest announcements from governments and world spectrum regulators, the first 5G in mmWave bands systems are expected to be implemented in the 26 GHz (3GPP n258), 28 GHz (3GPP n257 and n261), and 39 GHz (3GPP n260) bands [4].

Moreover, as mentioned before, one of the main advantages of 5G is the PHY layer flexibility, which uses different configurations depending on the scope of the application. One of the key parameters to define the 5G waveform is the subcarrier spacing (SCS). SCS is defined from a set of possible numerologies (μ) as follows:

$$SCS(kHz) = 15 \cdot 2^\mu \quad (1)$$

where μ represents numerology and can be 0, 1, 2, 3, or 4. As shown in Table I, the numerology also defines the slot duration and the symbol length. Furthermore, these parameters present the opposite behavior if compared with SCS. That is, the higher the SCS, the shorter the slot and symbol durations.

One of the consequences of using high frequencies is that the Doppler shift is also increased. To avoid a negative impact on the received signal, it is recommended to use high μ configurations ($\mu = 3$ or $\mu = 4$) [17]. These configurations imply that the minimum SCS is 120 kHz and that the symbol time, including the Cyclic Prefix (CP), does not exceed 10 μ s.

As shown in Table I, the numerology also determines the maximum bandwidth that can be used in each case. Except for $\mu = 4$, the maximum number of RBs that can be reserved in the rest of the cases is 275 (for $\mu = 4$, it is 138). The following expression is used to calculate the maximum bandwidth in each case:

$$BW = NRB \cdot BW_{RB} = NRB \cdot 12 \cdot SCS \quad (2)$$

where NRB is the number of RB allocated and BW_{RB} is the bandwidth of a single RB, which is equal to the size of 12 subcarriers separated SCS kHz. Therefore, following the recommended configurations for the mmWave bands, the maximum bandwidths offered are close to 400 MHz. Moreover, in FR2, channels can be aggregated, increasing the overall bandwidth.

Lastly, it should be remarked that the 5G waveform configurations for the mmWave bands affect the RRM process. In particular, as high numerologies have to be used, the symbol time is short, and, consequently, the Transmission Time Intervals (TTIs) are shorter. Therefore, RRM algorithms must guarantee a balance between performance and frequency of execution. For this reason, in general, RRM algorithms can

be classified into Fast RRM since they are executed in each TTI, and Slow RRM, which are those that are executed with a lower frequency [18].

B. Propagation Challenges

The propagation channel is a challenge in itself for any wireless communication medium. Most communication systems have been implemented below 6 GHz, and, therefore, there is extensive knowledge. However, in the case of the mmWave bands, some behaviors/effects are different from those assumed so far. Therefore, this section summarizes the main characteristics and differences of the propagation channels of the mmWave bands with respect to traditional microwave systems.

One of the main consequences of the increase in frequency is that the path losses grow considerably. Specifically, taking free space losses as a reference, increasing the frequency by an order of magnitude (i.e., $\times 10$) implies having an additional 20 dB of losses. However, since path losses do not depend solely on frequency, there are propagation models for different frequency ranges. Regarding the mmWave bands, the 3GPP TR 38.901 [19] channel model models different path losses depending on the application scenario. Among them, the models Urban Microcells (UMi) and Urban Macrocells (UMa) represent traditional cellular networks, and Indoor Hotspot (InH) and Indoor Factory (InF) are used for different indoor facilities. Fig. 1 shows the evolution of path losses as a function of distance for the UMi and UMa models, assuming Line-of-Sight (LOS) and non-LOS (NLOS), for the 30 GHz band (Fig. 1(a)) and the 60 GHz band (Fig. 1(b)). Furthermore, in [19], the probability of having LOS conditions is also modeled as a function of the scenario. In particular, these probability distributions have a negative exponential trend, and the UMa model has a higher probability of having a LOS condition than the UMi model.

Another vital factor in mmWave bands is that as they have smaller wavelengths than microwaves, they are more sensitive to obstacles [20]. Specifically, according to [21], obstacles in indoor environments or walls show higher penetration losses in the mmWave bands. In addition, when placing objects between the transmitter and the receiver in the mmWave bands communications, the characteristics of the channel vary considerably, and the shadowing effects are very damaging. The deterioration of the signal due to meteorological causes is another effect due to the wavelength size. In particular, when exceeding 10 GHz, meteorological effects such as rain, hail, or snow cause attenuations that must be taken into account [22].

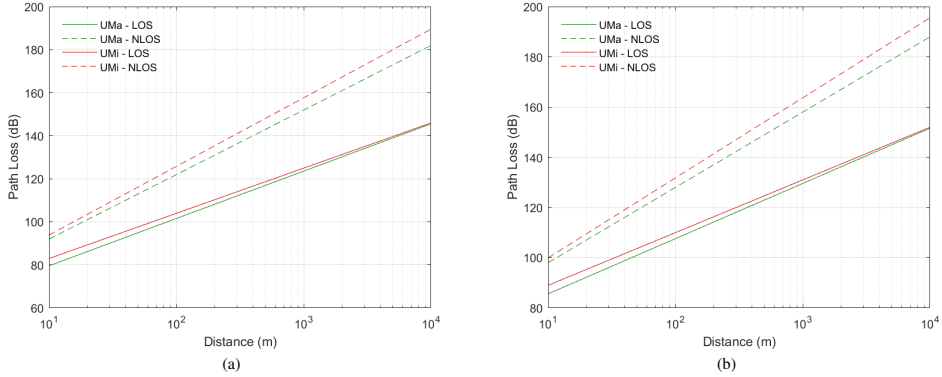


Fig. 1: Path loss attenuation following 3GPP TR 38.901 for different frequency bands: (a) 30 GHz, (b) 60 GHz.

C. Benefits & Drawbacks

One of the main benefits of the mmWave bands is the increase in capacity offered because the available bandwidths are much higher than those of sub-6GHz bands. This effect is reflected in two parameters: the number of users served, and the throughput offered. Specifically, the first parameter is analyzed in more detail in Table II.

To carry out the analysis, two typical bandwidths of 5G communications in the sub-6GHz bands (i.e., 50 and 100 MHz) and two other bandwidths related to the mmWave bands (i.e., 400 MHz and 1 GHz) have been chosen. In addition, since they determine the transmitted throughput, three MCS values have also been selected according to Table 5.1.3.1-2 in [23]: the minimum (i.e., MCS0, QPSK 120/1024), an intermediate one (i.e., MCS14, 64QAM 616/1024) and the maximum (i.e., MCS28, 256QAM 948/1024). Then, in order to contextualize the analysis, three relevant use cases for the future 5G communications with completely different capacity constraints have been used as reference. The first is Internet of Things (IoT), and the characteristics defined in the Rel-13 (Narrow Band IoT) have been taken into account, where a maximum data rate of 200 kbps per user in downlink channels is allowed [24]. The second is the reception of video content in mobile and portable devices, which, according to [25], a minimum data rate of 2 Mbps is required for high-quality video content. Finally, AR/VR applications have been used due to their promising future. In this case, the necessary capacity is usually related to a wide range, where the highest quality applications can reach up to 100 Mbps and the ones of basic qualities between 20 and 30 Mbps [26]. For the analysis, 25 Mbps has been chosen as a potential representative value of the mobile AR/VR applications. As it can be seen in Table II, the increase in bandwidth leads to a proportional increase in the number of users served, which occurs in applications based on mmWave bands. In fact, the number of users served on the channels oriented to the mmWaves bands is considerably higher regardless of the MCS used. In addition, it should be

noted that if due to the channel or application conditions, it is necessary to use the most robust MCS, the performance obtained with the channels of the sub-6GHz bands is very limited (e.g., it is not possible to implement AR/VR). In contrast, in the mmWave bands, access to a relevant number of users in each case can be guaranteed.

On the contrary, the main disadvantages of mmWave bands are the consequences derived from the increase in the path losses suffered by the transmissions. Therefore, to compensate more gNBs must be entered in the mmWave bands than in the sub-6GHz bands. For example, taking as a reference a network with a coverage radius of 1km (i.e., an area of 3140 km²) and a central frequency of 2 GHz, if it is assumed that the path loss model that affects it is the UMa-LOS shown in Section III-B, the path loss at the edge of the cell is 100 dB. However, if the network is based on 30 GHz transmissions and the same path loss value must be guaranteed, the cell edge is located at 85 meters with an area of 22.7 km². Consequently, the number of gNBs needed to cover that area would be 138 times greater.

Undoubtedly, due to the presented facts, mmWave bands can be considered ideal for creating small networks (e.g., picocells or femtocells) where additional network access should be guaranteed or additional capacity has to be offered.

D. Potential Applications

The increase in the frequency of implementation of 5G services and, as a consequence, the considerable increase in the channel bandwidths used allows challenging applications to be possible. This subsection shows some of the applications that will possibly be implemented in the 5G mmWave bands.

One of the straightforward applications of 5G mmWave bands is to offer traditional broadband applications with considerably enhanced qualities [27]. For example, applications that require high data rates such as AR/VR content, 4k/8k video content, or 360° video streaming may be easier to implement on the mmWave bands.

TABLE II: Analysis of the maximum number of users that could be served using different bandwidth sizes for different applications

MCS	Efficiency	Application	Constraint	Users in 50 MHz	Users in 100 MHz	Users in 400 MHz	Users in 1 GHz
MCS0	0.2344 bps/Hz	NB-IoT	200 kbps	58	117	468	1172
		Mobile HD video	2 Mbps	5	11	46	117
		AR/VR	25 Mbps	0	0	3	9
MCS14	3.6094 bps/Hz	NB-IoT	200 kbps	902	1804	7218	18047
		Mobile HD video	2 Mbps	90	180	721	1804
		AR/VR	25 Mbps	7	14	57	144
MCS28	7.4063 bps/Hz	NB-IoT	200 kbps	1851	3703	14812	37031
		Mobile HD video	2 Mbps	185	370	1481	3703
		AR/VR	25 Mbps	14	29	118	296

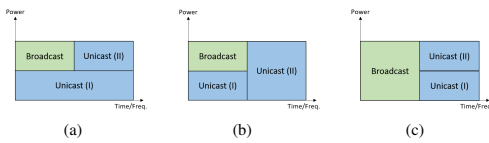


Fig. 2: Representation of the proposed RRM schemes: (a) Model A, (b) Model B, (c) Model C.

Another possible application is to use the 5G mmWave bands to guarantee access to content in high-attendance environments [28]. Stadiums, concerts, exhibitions, or festivals are clear examples of locations where the density of users is very high and traditional networks are not always capable of serving all users correctly. Therefore, using the 5G mmWave bands in specific areas with large bandwidths considerably reduces the possibility of network saturation. Furthermore, this alternative could be used in combination with existing small networks or could replace the access networks of certain places.

Finally, the use of the 5G mmWave bands for backhaul applications should be highlighted [29]. Although fiber optics systems have traditionally been used for the backhaul of wireless networks, the reduction in the coverage area in the mmWave bands and the increase in the number of networks generates an increase in the cost of implementation and scalability that may not be assumable. Therefore, using frequency bands above 6 GHz for the backhaul is a real alternative. In particular, the use of 60 GHz unlicensed bands with LOS conditions for backhaul applications is under study [28].

IV. PROPOSED RRM SCHEMES

As mentioned in [8], pure TDMA and pure NOMA RRM schemes can be considered suboptimal solutions, and the design of combined TDMA and NOMA RRM solutions should provide better performance rates. Therefore, the objective of this section is to propose different combined RRM schemes.

In this work, three different RRM schemes are proposed, and Fig. 2 presents the representation of each model. In general, each of the models is based on three different blocks: broadcast, unicast (I), and unicast (II). It should be noted that the unicast (I) and unicast (II) blocks are a set of resources dedicated to the transmission of unicast services, so each of the blocks is divided into multiple individualized unicast services. The main difference between the three models is

the combination of the multiplexing schemes. For example, Model A (see Fig. 2(a)) is based on a NOMA scheme where the Upper Layer (UL) is TDMized to distribute the resources between the broadcast service and one of the unicast blocks. The main benefit of this model is that channel resources are distributed twice, once for the UL and once for the Lower Layer (LL). However, the SNR associated with decoding each of the services will assume a penalty for being a NOMA-based transmission. On the other hand, Model B (see Fig. 2(b)) presents a TDMA scheme where in the first part NOMA is applied to multiplex the broadcast service and a block of unicast services with the same number of resources as the broadcast block. In this case, the unicast block (II) is transmitted in single-layer mode, so the required SNR per user will be lower than in Model A, but not all the resources are available. Finally, Model C (see Fig. 2(c)) is another TDMA model where NOMA has been applied to multiplex the two blocks of unicast content. This model presents the most robust broadcast service; since it is configured in single-layer mode, its associated SNR is the lowest. However, the use of the spectrum is lower than in the case of Model A.

Algorithm 1 shows a five-step generalization of the RRM schemes presented above. It should be mentioned that the RRM schemes are designed so that they can be executed in each TTI. The first step consists in obtaining feedback from each user. In this case, the feedback is the CQI (i.e., u_k) perceived by each k^{th} user connected to the gNB. By gathering each feedback, the Channel Quality Indicator (CQI) distribution vector $U = \{u_1, u_2, \dots, u_K\}$ is generated, being K the total number of users in the network.

Then, the three steps related to configuring the three service blocks are executed for all the Injection Level (IL) values, where $l = \Delta_1, \dots, \Delta_L$ represents the set of possible IL values. In order to set the range of possible ILs, the same range as in ATSC 3.0 has been used [30]. It is composed of 31 values, where steps of 1 dB are used for IL between -25 dB and -5 dB and steps of 0.5 dB between -5 dB and 0 dB. First, the broadcast service is configured in Step 2. To do so, the RRM scheme calculates, according to the minimum broadcast capacity constraint, the required number of resource blocks (BW_{BR_l}). It should be noted that the BW_{BR_l} calculation varies depending on if the broadcast block is configured in single-layer or the UL of a two-layer system. In particular, in the case of Model C, the BW_{BR_l} calculation is directly carried out with the SNR related with the CQI values. In contrast, in Models A and B, the SNR required to obtain each CQI has

Algorithm 1 Common steps of the proposed RRM schemes

```

1: Define:  $l = \Delta_1, \dots, \Delta_L$ . Set of possible ILs;
2: Define:  $tti = 1, \dots, TTI$ . Set of evaluated TTIs;
3: for  $tti \leq TTI$  do
4:   Step 1 - CQI acquisition:
        $U = \{u_1, u_2, \dots, u_K\}$ 
5:   for  $l \leq \Delta_L$  do
6:     Step 2 - Broadcast service configuration:
        $BW_{BR_l}, eff_{BR_l}, th_{BR_l}$ 
7:     Step 3 - Unicast service configuration in block
       (I):
        $[BW_{UN_{1,l}}, eff_{UN_{1,l}}, th_{UN_{1,l}}] \dots$ 
        $[BW_{UN_{N,l}}, eff_{UN_{N,l}}, th_{UN_{N,l}}]$ 
8:     Step 4 - Unicast service configuration in block
       (II):
        $[BW_{UN_{N+1,l}}, eff_{UN_{N+1,l}}, th_{UN_{N+1,l}}] \dots$ 
        $[BW_{UN_{N+M,l}}, eff_{UN_{N+M,l}}, th_{UN_{N+M,l}}]$ 
9:   end for
10:  Step 5 - Get the configuration that maximizes
     unicast aggregated throughput:
        $\max_l \sum_{i=1}^{N+M} th_{UN_{i,l}}$ 
11: end for

```

to be recalculated since they assume a penalization due to the two-layer structure. The SNR adaptation for the UL has been carried out according to [DCAN], and [31]. Then, the throughput of the broadcast service (th_{BR_l}) is calculated as follows:

$$th_{BR_l} = BW_{BR_l} * eff_{BR_l} \quad (3)$$

eff_{BR_l} is the efficiency of the transmitted service (bps/Hz), which is obtained from the selected MCS value according to Table 5.1.3.1-2 in [23].

In Step 3, the first block of the unicast services is configured. In this work, it should be noted that it has been decided to start serving the unicast users through the unicast blocks located at the LL. Through simulations, it has been proven that this structure gives better results than starting serving unicast users through simulations of the blocks in the UL or single-layer. One of the main differences among the RRM models is the RB dedicated to each unicast service configuration block. Concretely, the three models have a different amount of resources ($BW_{UN(I)}$) in Step 3. In the case of Model A, as the unicast block (I) is extended during the whole bandwidth, the amount of resources is equal to the total amount of RB in the channel (BW_{TOT}). On the contrary, both Model B and Model C have a limited amount of resources. In fact, while in Model B $BW_{UN(I)}$ is equal to BW_{BR} , in Model C is calculated as follows:

$$BW_{UN(I)} = BW_{TOT} - BW_{BR} \quad (4)$$

Once the total number of RBs available for the unicast block (I) has been determined, the RRM scheme begins to serve users one by one. In this case, users are served based on the feedback sent so that users with better CQIs are managed first

since they require fewer RBs than users with bad CQI, and access to a greater number of users can be guaranteed. In order to configure the service to each user, the requested CQI is taken as a reference to decide the number of RBs required for each user ($BW_{UN_{l,k}}$). Then, similar to Eq. (3) the throughput delivered to the k^{th} user using the l^{th} IL is calculated. As in the case of the broadcast service, an SNR adaptation has to be applied since the SNR associated with the requested CQI value has been calculated in single-layer mode, and the unicast services delivered in the first unicast block are organized in the LL. Also in this case, the LL SNR adaptation is based on the procedure defined in [DCAN], and [31]. Then, in the first unicast block, the CQI value for the LL is selected to guarantee that the SNR required for the LL is equal to or less than the required in single-layer mode. When the configuration for the k^{th} user is managed, the number of RBs available for unicast block (I) is updated by subtracting the resources allocated to the previous user:

$$BW_{UN(I)} = BW_{UN(I)} - BW_{UN_{l,k}} \quad (5)$$

Then, the algorithm checks if there are available RBs to continue with the resource allocation of the first block ($BW_{UN(I)} > 0$). If there are still available RBs, the following user (i.e., $k + 1$) in U is served. If not, the RRM algorithm goes to Step 4.

For its part, configuring the services of the unicast block (II) is similar to the process described in Step 3. In this case, the first user to be served is the user $N+1$, N being the last user to be served entirely in the unicast block (I). If, on the other hand, the user N has not been fully served in the previous block, before starting to serve $N + 1$, the missing throughput of N is completed. Afterward, the same process as shown in Step 3 is repeated, but taking into account in the SNR adaptation process that the unicast block (II) is not located in the LL. In fact, SNR adaptation is necessary only in Models A and C since the unicast service is transmitted on the UL. In Model B, no adaptation is required because the transmission of the unicast services is carried out in single-layer mode. Once all the resources dedicated to the unicast block (II) are finished ($BW_{UN(II)} \leq 0$), all the user configurations are saved, and the following IL is evaluated ($l+1$). At this point, M represents the number of users served in the second unicast block and $N + M$ the total number of unicast users served.

The resource allocation process is repeated until the calculations are completed for all the ILs described in l , and, in the last step (i.e., Step 5), the best performing configuration is selected. In this case, the throughput of the unicast services is determined as the optimization parameter. Therefore, the best performing configuration is determined by looking for the configuration that has the highest aggregate unicast throughput:

$$\max_l \sum_{i=1}^{N+M} th_{UN_{i,l}} \quad (6)$$

V. EVALUATION USE CASE

The objective of the selected use case to evaluate the RRM schemes shown in the previous section is to provide service

in a high occupancy environment. A museum room is taken as a reference where many people accumulate in a reduced environment. The service offered is a mixed broadcast/unicast mode. Firstly, the primary content will be transmitted through the broadcast service. Each user in the room can access a common online platform where the physical distribution of the room and the list of additional content that can be requested are detailed. Then, the goal of the unicast service is to customize/personalize the service that the user is receiving. For this, the unicast service may be video content with additional explanations of the works of art, AR content to interact with the exhibition, or interactive games about additional data about the content of the exhibition hall. To guarantee the correct functioning of the application, users must have access to the broadcast service ensured, and the application has to provide on-demand content to the largest possible number of users.

Concerning the services, the needs of broadcast and unicast services are different in terms of various parameters. On the one hand, the broadcast service must guarantee the download of the application to all users in the room so that it will be encoded with the lowest possible Modulation and Code Scheme (MCS), MCS0 (QPSK 120/1024) [23]. In addition, the minimum capacity that must be offered will range between one and ten Mbps, depending on the type of content in the download (data, images, video, etc.) and the type of end-user (mobile, tablet, laptop, etc.). In contrast, the unicast personalization service does not have as strict accessibility requirements as the broadcast service, so the service will be encoded based on the Channel Quality Indicator (CQI) received from the user. Regarding the minimum capacity to offer, a range from three to 30 Mbps will be studied in order to include in the study from services with low requirements (video content to small screen mobile devices) to more demanding services such as AR applications on tables with large high definition screen displays.

In order to carry out the simulations, OMNeT++ has been used [32], which is a packet simulator. In this simulator, a room of 30x30 meters and 3 m height has been defined, representing the room where the works of art and service receiver users are concentrated. A transmitter has been placed on the room ceiling (i.e., 3 m transmitter antenna height), and the receivers have been randomly distributed throughout the room. The receivers are pedestrians that move at an average speed of 3 km/h following the Random Waypoint Point (RWP) mobility model [33], which emulates the movements of pedestrians. The central frequency used to offer the service is 28 GHz, and a bandwidth of 400 MHz is used to provide broadcast and unicast services among all users. To represent propagation, the indications described in [19] for indoor environments have been followed. In this case, the path loss model used is described in Table III and taking into account the typical layout of the showrooms and that the transmitter is located on the ceiling, Line-of-Sight (LOS) condition is assumed. Regarding the propagation channel, following the indications in [19], the TDL-D and TDL-E (Tapped Delay Line) profiles are used to model the channels with a short delay spread of 16 ns and a shadowing effect with a mean zero and σ 3 dB. Finally, it should be noted that the designed RRM algorithms are

TABLE III: Use case parameters

Parameter	Value
Center Frequency	28 GHz
Bandwidth	400 MHz
SCS	120 kHz
Tx Power	24 dBm
BS Antenna Height	3 m
RX Antenna Height	1.5 m
LOS/NLOS	LOS
Path Loss	InH model in [19]
User Type	Pedestrians
Number of Users	Up to 320
Speed	3 km/h
Mobility Type	RWP
Hall Size	30m x 30m x 3m
Desired Delay Spread	16 ns
Channel Model	TDL-D, TDL-E
Shadowing	$\sigma = 3$ dB
Noise Power	-90 dBm
Noise Figure	9 dB
RRM Frequency	1 ms
Broadcast Service Capacity	1-10 Mbps
Unicast Service Capacity	3-30 Mbps/user

executed with a frequency of one ms (each subframe). That is, during the resource allocation phase, all the RBs contained in a subframe are distributed.

The rest of the use case parameters are shown in Table III.

VI. RESULTS

This section evaluates the performance of the RRM schemes shown in Section IV under the evaluation use case defined in V. First, the evaluation metrics are introduced and, then, the results are discussed.

A. Evaluation Metrics

In this work, the performance of the proposed RRM algorithms will be evaluated from the throughput and number of users served perspective. Next, the characteristics of each parameter are shown.

Regarding capacity, two parameters will be used. The first is the throughput per service, which is a double parameter that defines the datarate dedicated to the broadcast service and the unicast service. The throughput of the broadcast service (th_{BR}) is calculated in Eq. (3). The objective of the th_{BR} is to show if the RRM algorithm is capable of adjusting the offered capacity to the minimum throughput requirement imposed by the application. In contrast, unicast service throughput (th_{UN}) measures the volume of unicast traffic on the network and is calculated as the sum of all the individual unicast services offered:

$$th_{UN} = \sum_{i=1}^N th_{UN_i} = \sum_{i=1}^N BW_{UN_i} * ef_{UN_i} \quad (7)$$

where, i is the unicast user index, N is the amount of served unicast users, and th_{UN_i} is the individual throughput value of i^{th} unicast user, which is calculated as in (3), but following the bandwidth allocated for each user (BW_{UN_i}) and the efficiency decided for each user (ef_{UN_i}). Then, the other parameter related to the capacity measurement is the ADR, representing

the sum of all the data received by each user. It is defined as follows:

$$ADR = th_{BR} * \sigma + th_{UN} \quad (8)$$

where, σ represents the number of users able to decode the broadcast service correctly.

To evaluate the algorithm performance in terms of the number of users served, two other metrics will be used. On the one hand, availability will be used as a robustness measure for the broadcast service. Availability measures the number of users who can receive the common service correctly with respect to the total number of users. To ensure that users can access the application fluently, availability must be above 95%. On the other hand, the number of users that can be served simultaneously with the personalized unicast service will also be measured. In this case, the unicast user number served in each configuration will be presented directly. It should be noted that the personalized service is a non-priority service, so the number of users that will be given access will be considerably less than in the case of the broadcast service.

B. NOMA-only and TDMA-only modes

This subsection aims to analyze the performance of RRM schemes based on a single technique (NOMA-only or TDMA-only) in the use case proposed above. For this, Table IV presents the results obtained in terms of throughput for both services (th_{BR} and th_{UN}), the number of unicast users served, and the ADR.

First, it should be noted that the results of NOMA-only do not adapt to variations in the capacity requirements of the broadcast service. This effect occurs because the entire bandwidth (i.e., 400 MHz) is used for the broadcast service, which is much higher than the requirements established by the use case. On the contrary, variations in the unicast service requirement cause a slight reduction in th_{UN} and a considerable decrease in the number of users served. On the other hand, the TDMA-only algorithm does allow the services offered to be adapted according to the application requirements. For this reason, the th_{BR} adapts to the minimum to offer and allows the th_{UN} and the number of unicast users served to be better than those offered by NOMA-only. Finally, it is necessary to emphasize the difference in the ADR results. NOMA-only offers around ten times more ADR than TDMA-only in all cases. This effect is caused because with NOMA-only, it is not possible to adapt the th_{BR} to the imposed requirements, and the capacity offered is well above what is requested, which causes extremely high ADR values. However, this data is not representative since the difference does not indicate an improvement compared to TDMA-only, but rather a misuse of available resources.

Undoubtedly, these results agree with the conclusions described in [8] and [DCAN], where it is shown how the schemes that use NOMA-only are not capable of adapting to the use case requirements. However, in [8] and [DCAN], the mmWave bands are not used, and, therefore, the bandwidths are smaller, which makes the differences between NOMA and TDMA not as evident as in this case. In fact, in sub-6 GHz applications, NOMA still outperforms TDMA, but using larger channels

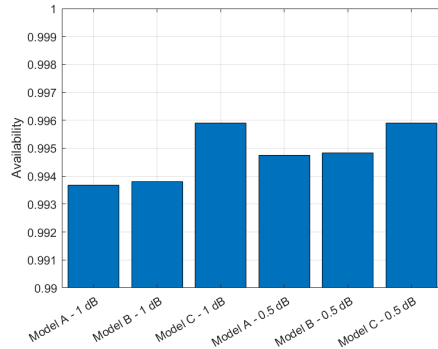


Fig. 3: Availability results of the proposed RRM methods.

is more detrimental to NOMA-only schemes. Therefore, it seems that the RRM schemes that can approach the optimal distribution of resources are those that combine TDMA and NOMA. In this way, the ability to adapt to the application requirements that TDMA offers can be combined with the improvement in spectral efficiency that NOMA provides.

C. Combined RRM algorithms

First, the availability values are presented since it is the primary condition to receive the rest of the services correctly. Availability results are shown in Fig. 3 for all models with two different UL SNR penalties (0.5 dB and 1 dB). It should be noted that the variation in the requirements of broadcast and unicast services hardly affects availability, so the values shown in Fig. 3 are average values of all the TTIs. First of all, it must be emphasized that all the values are above 99% so that they are all valid results. Among all the models, as expected, the one that offers the best availability is Model C. The main reason is that the broadcast service is implemented in SL mode, it has lower SNR than Models A and B, and it is not affected by the UL SNR penalty. However, the difference between the other two models is slight and assumable. Also, as expected, on Models A and B, availability is increased by reducing the UL SNR penalty. Based on the above-shown results, a UL SNR penalty of 1 dB will be used in the rest of the results since it has a similar availability rate to 0.5 dB.

The number of unicast users served is shown in Fig. 4 for three different broadcast service requirements: three Mbps (see Fig. 4(a)), six Mbps (see Fig. 4(b)) and nine Mbps (see Fig. 4(c)). As can be seen, Models A and C are once again the ones with the best performance, with very similar results. Also, Model B shows worse performance than the other two models. Regarding the service requirements, the broadcast requirement hardly interferes with the results. In contrast, the minimum unicast service requirement does have an impact on the number of users served, especially in Model B, which is the one that decreases the most rapidly. If the requirements of unicast services are related to real personalization services, services related to video applications would be below ten Mbps, while

TABLE IV: Throughput, served unicast users and ADR results of NOMA-only and TDMA-only RRM schemes for different broadcast and unicast service requirements

Minimum Broadcast Service	Minimum Unicast Service	NOMA-only				TDMA-only			
		th_{BR} (Mbps)	th_{UN} (Mbps)	Unicast Users	ADR (Mbps)	th_{BR} (Mbps)	th_{UN} (Mbps)	Unicast Users	ADR (Mbps)
3 Mbps	6 Mbps	92.82	1276.57	202.50	30822.35	3.04	1914.38	293.72	2882.49
	12 Mbps	92.82	1539.29	122.46	31085.07	3.04	2610.01	200.77	3578.12
	24 Mbps	92.82	1545.31	63.00	31091.09	3.04	2835.50	112.05	3803.61
6 Mbps	6 Mbps	92.82	1276.57	202.50	30822.35	6.03	1893.11	290.24	3815.88
	12 Mbps	92.82	1539.29	122.46	31085.07	6.03	2545.45	195.61	4468.22
	24 Mbps	92.82	1545.31	63.00	31091.09	6.03	2741.47	109.98	4664.24

those oriented to AR applications between 20 and 30 Mbps. In the case of videos with Models A and C, practically all users could receive them (minimum 300 users), while with Model B, the service could be guaranteed to about 250 users. On the contrary, for AR-based applications, Models A and C show that they can serve 50% more users since they guarantee access to around 150 users, while with Model B, it would not reach 100 users.

Concerning the throughput results, first, Table V shows the throughput results per service that have been obtained with each of the RRM models for different broadcast and unicast requirements. As can be seen, the th_{BR} obtained in all cases is adjusted to the minimum required by the application, unlike the NOMA cases shown in the previous subsection. Also, the th_{UN} shows a considerable increase when the minimum unicast throughput per user increases. On the contrary, when increasing the broadcast service requirement, the th_{UN} presents a slight reduction. This effect indicates that the RBs reserved to cover the broadcast service are very few compared to those that remain to serve the unicast users and, therefore, it hardly affects the results. When comparing the results based on the models, it is seen that Model B is less efficient since it is capable of offering a much lower th_{UN} than Models A and C. In the configuration with the most significant difference (minimum broadcast service 3 Mbps and minimum unicast service 24 Mbps), models A and C improve the performance of Model B by almost 60%. The best results are found in Model A since it offers values of th_{UN} slightly higher than Model C, up to 4% better in some cases.

Then, the ADR results for each RRM model are shown in Fig. 5, where the minimum broadcast services are 3 Mbps, 6 Mbps, and 9 Mbps in Fig. 5(a), Fig. 5(b), and Fig. 5(c), respectively. As in the throughput case, the ADR results also show that Model B has a significantly lower performance than Models A and C. However, the difference between the models is reduced, since the performance difference between Model A and Model B in Fig. 5 (a) is around 30%, while in the case of Fig. 5 (c) it does not exceed 22%. Likewise, the difference in performance between Models A and C also increases as the requirement for broadcast service grows, indicating that Model A always offers the best ADR result. The different trends shown by the curves should also be highlighted since they have, first, a phase of exponential increase and, then, a saturation phase. The exponential increase occurs because increasing the unicast service requirement does not imply a linear decrease in users number. In fact, as explained in Section IV, by serving the users with the best conditions first,

the first users who are left out of the personalization service are the users who require more RBs, since they request low MCS values. Therefore, as the unicast service requirement increases, the efficiency of the services offered increases, and the ADR grows. On the contrary, in the saturation phase, this effect does not occur. In the case of saturation, the users with the worst conditions have already been rejected, and those who are served have good channel conditions, so the increase in the minimum unicast service practically implies a linear reduction in the number of users served. Finally, it is worth highlighting the ADR result obtained for Models A and C between three and six Mbps of unicast service. In those cases, despite increasing the unicast service, the ADR hardly changes. This effect is because in the case of three Mbps, all users are served once and the RRM model performs a second round in serving the majority of users during the same TTI. So as the requirement of the unicast service increases, the users that are left out are those that had been served a second time, that is, those with good channel condition. Consequently, the total spectral efficiency falls, and the ADR does not grow. This effect does not occur in Model B because it presents a less efficient use of resources. It does not serve as many users in the second round as Models A and C. Therefore, the effect is less noticeable and does not present such an abrupt change in the behavior. However, it can be seen that in Model B, the increase from three to six Mbps is less than the increase from six to nine Mbps.

Finally, when comparing the results shown in this subsection with those obtained with the NOMA-only and TDMA-only schemes (see Section VI-C), it can be seen that Models A and C improve all KPIs and that Model B is slightly better. Specifically, both Model A and Model C improve the results shown in Table IV by around 50%. Especially, the difference increases when the requirements of broadcast and unicast services increase. Therefore, as a summary, it should be noted that the RRM schemes that combine TDMA and NOMA considerably improve the performance of the simple models and that, in particular, Models A and C are the best possible options.

VII. CONCLUSIONS

This article considers resource allocation techniques that combine TDMA and NOMA to improve spectral efficiency in applications implemented in the mmWave bands. For this, three different RRM models have been designed and evaluated in terms of throughput (th_{BR} and th_{UN}), capacity (number of unicast users served), and availability. In addition, they

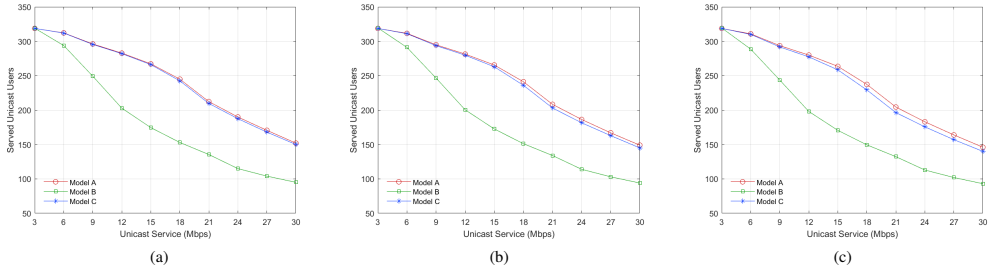


Fig. 4: Number of served unicast users for different minimum broadcast capacity values: (a) 3 Mbps, (b) 6 Mbps, (c) 9 Mbps.

TABLE V: Obtained throughput per service results for different broadcast and unicast requirements

Minimum Broadcast Service	Minimum Unicast Service	Model A		Model B		Model C	
		th_{BR} (Mbps)	th_{UN} (Mbps)	th_{BR} (Mbps)	th_{UN} (Mbps)	th_{BR} (Mbps)	th_{UN} (Mbps)
3 Mbps	6 Mbps	3.04	2041.48	3.04	1920.58	3.04	2038.11
	12 Mbps	3.04	3500.97	3.04	2645.89	3.04	3493.16
	24 Mbps	3.04	4630.19	3.04	2896.99	3.04	4570.80
6 Mbps	6 Mbps	6.03	2025.62	6.03	1904.30	6.03	2020.03
	12 Mbps	6.03	3483.70	6.03	2614.94	6.03	3467.22
	24 Mbps	6.03	4543.06	6.03	2870.12	6.03	4423.98
9 Mbps	6 Mbps	9.03	2011.39	9.03	1887.28	9.03	2004.64
	12 Mbps	9.03	3465.86	9.03	2584.45	9.03	3439.82
	24 Mbps	9.03	4455.26	9.03	2835.19	9.03	4275.34

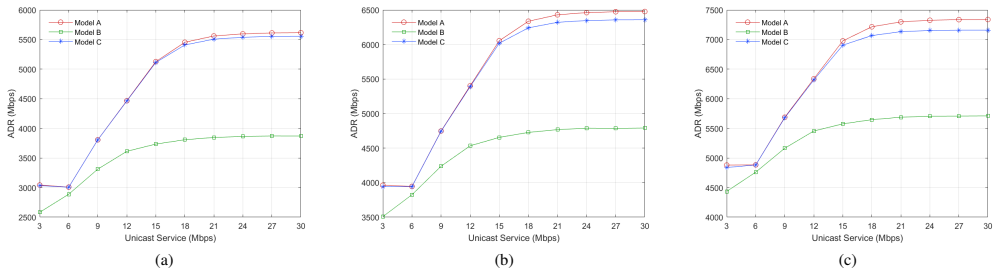


Fig. 5: ADR results for different minimum broadcast capacity values: (a) 3 Mbps, (b) 6 Mbps, (c) 9 Mbps.

have been compared to schemes that only implement one of the multiplexing mechanisms (only-NOMA and only-TDMA), and the improvement is considerable. Moreover, the main challenges and possible applications of 5G in the mmWave bands have also been highlighted, and an innovative use case has been designed to test the designed RRM schemes.

Regarding the results, it has been verified that the RRM schemes that combine TDMA and NOMA considerably improve the schemes of a single multiplexing mechanism. Especially when the application requirements are high, the difference in performance exceeds 50%. Concerning the RRM models designed, it should be noted that even Model B has acceptable performance, Models A and C outperform Model B in all KPIs. Furthermore, the results indicate that for the proposed use case, using Models A and C, in the case of additional high-quality videos, access to the personalization

service can be guaranteed to around 300 users (almost all the users in the cell). In contrast, in AR services, a minimum of 150 users is guaranteed with Models A and C. Finally, it should be highlighted that Model A outperforms Model C slightly since Model A downgrades less the results when the broadcast and unicast requirements are increased.

ACKNOWLEDGMENT

This work has been partially supported by the Basque Government (the grant IT1234-19 and the PREDOC grant program PRE_2020_2_0105) and by the Spanish Government (project PHANTOM under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE)).

REFERENCES

- [1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022.

- [2] ITU-R Rec. ITU-R M. 2083-0, "IMT Vision — Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," Sept. 2015.
- [3] 3GPP TS 38.201 v15.0.0, Tech. Spec. Group Services and System Aspects, "NR; Physical layer; General description," Tech. Rep., Jan. 2018.
- [4] A. V. Lopez, A. Chervyakov, G. Chance, S. Verma, and Y. Tang, "Opportunities and challenges of mmwave nr," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 4–6, 2019.
- [5] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H. M. Kim, J.-Y. Lee, P. Angueira, and J. Montalbán, "Layered-division-multiplexing: Theory and practice," *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 216–232, 2016.
- [6] J. Montalbán, P. Scopelliti, M. Fadda, E. Iradier, C. Desogus, P. Angueira, M. Murrioni, and G. Araniti, "Multimedia multicast services in 5g networks: Subgrouping and non-orthogonal multiple access techniques," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 91–95, 2018.
- [7] E. Iradier, J. Montalbán, L. Fanari, P. Angueira, L. Zhang, Y. Wu, and W. Li, "Using noma for enabling broadcast/unicast convergence in 5g networks," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 503–514, 2020.
- [8] E. Iradier, A. Abuin, L. Fanari, J. Montalbán, P. Angueira, L. Zhang, W. Li, and Y. Wu, "Broadcast/unicast convergence in noma-based 5g: a rrm optimization algorithm," in *2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, 2020, pp. 1–6.
- [9] S. Scott-Hayward and E. Garcia-Palacios, "Multimedia resource allocation in mmwave 5g networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 240–247, 2015.
- [10] A. Samouylov, D. Moltchanov, R. Kovalchukov, R. Pirmagomedov, Y. Gaidamaka, S. Andreev, Y. Koucheryav, and K. Samouylov, "Characterizing resource allocation trade-offs in 5g nr serving multicast and unicast traffic," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 3421–3434, 2020.
- [11] R. Liu, Q. Chen, G. Yu, and G. Y. Li, "Joint user association and resource allocation for multi-band millimeter-wave heterogeneous networks," *IEEE Transactions on Communications*, vol. 67, no. 12, pp. 8502–8516, 2019.
- [12] J. Deng, O. Tirkkonen, R. Freij-Hollanti, T. Chen, and N. Nikaiein, "Resource allocation and interference management for opportunistic relaying in integrated mmwave/sub-6 ghz 5g networks," *IEEE Communications Magazine*, vol. 55, no. 6, pp. 94–101, 2017.
- [13] N. Nouri, J. Abouei, M. Jaseemuddin, and A. Anpalagan, "Joint access and resource allocation in ultradense mmwave noma networks with mobile edge computing," *IEEE Internet of Things Journal*, vol. 7, no. 2, pp. 1531–1547, 2019.
- [14] Z. Shi, Y. Wang, L. Huang, and T. Wang, "Dynamic resource allocation in mmwave unified access and backhaul network," in *2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE, 2015, pp. 2260–2264.
- [15] S. Kumar, S. Suman, and S. De, "Dynamic resource allocation in uav-enabled mmwave communication networks," *IEEE Internet of Things Journal*, 2020.
- [16] C. K. Agubor, I. Akwukwuegbu, M. Olubiwe, C. O. Nosiri, A. Ehinomen, A. A. Olukunle, S. O. Okozi, L. Ezema, and B. C. Okeke, "A comprehensive review on the feasibility and challenges of millimeter wave in emerging 5g mobile communication," *Adv. Sci. Technol. Eng. Syst.*, vol. 4, no. 3, pp. 138–144, 2019.
- [17] A. A. Zaidi, R. Baldemair, V. Molés-Cases, N. He, K. Werner, and A. Cedergren, "Ofdm numerology design for 5g new radio to support iot, e-ub, and mbsfn," *IEEE Communications Standards Magazine*, vol. 2, no. 2, pp. 78–83, 2018.
- [18] Y. Li, E. Pateromichelakis, N. Vucic, J. Luo, W. Xu, and G. Caire, "Radio resource management considerations for 5g millimeter wave backhaul and access networks," *IEEE Communications Magazine*, vol. 55, no. 6, pp. 86–92, 2017.
- [19] 3GPP TR 38.901, Radio Access Network Working Group and others, "Study on channel model for frequencies from 0.5 to 100 ghz (release 15)," Tech. Rep., 2018.
- [20] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Melliós, and J. Zhang, "Overview of millimeter wave communications for fifth-generation (5g) wireless networks—with a focus on propagation models," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213–6230, 2017.
- [21] S. Sun, T. S. Rappaport, M. Shafi, P. Tang, J. Zhang, and P. J. Smith, "Propagation models and performance evaluation for 5g millimeter-wave bands," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 9, pp. 8422–8439, 2018.
- [22] ITU-R, "Specific attenuation model for rain for use in prediction methods, propagation in non-ionized media," Tech. Rep. P.838-3, 2005.
- [23] 3GPP TS 38.214 v15.3.0, Tech. Spec. Group Services and System Aspects, "NR; Physical layer procedures for data (Release 15)," Tech. Rep., Sept. 2018.
- [24] S. Persia and L. Rea, "Next generation m2m cellular networks: Lte-mtc and nb-iot capacity analysis for smart grids applications," in *2016 AEIT International Annual Conference (AEIT)*. IEEE, 2016, pp. 1–6.
- [25] X. Xu, J. Liu, and X. Tao, "Mobile edge computing enhanced adaptive bitrate video delivery with joint cache and radio resource allocation," *IEEE Access*, vol. 5, pp. 16406–16415, 2017.
- [26] M. S. Elbambay, C. Perfecto, M. Bennis, and K. Doppler, "Toward low-latency and ultra-reliable virtual reality," *IEEE Network*, vol. 32, no. 2, pp. 78–84, 2018.
- [27] K. Sakaguchi, T. Hausteijn, S. Barbarossa, E. C. Strinati, A. Clemente, G. Destino, A. Pärssinen, I. Kim, H. Chung, J. Kim *et al.*, "Where, when, and how mmwave is used in 5g and beyond," *IEEE Transactions on Electronics*, vol. 100, no. 10, pp. 790–808, 2017.
- [28] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Key elements to enable millimeter wave communications for 5g wireless systems," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 136–143, 2014.
- [29] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave communications (mmwave) for 5g: opportunities and challenges," *Wireless networks*, vol. 21, no. 8, pp. 2657–2676, 2015.
- [30] Advanced Television Systems Committee and others, "ATSC Standard: Physical Layer Protocol (A/322). Doc. A/322: 2106," *Washington, DC, USA*, 2016.
- [31] J. Montalbán, L. Zhang, U. Gil, Y. Wu, I. Angulo, K. Salehian, S.-I. Park, B. Rong, W. Li, H. M. Kim *et al.*, "Cloud transmission: System performance and application scenarios," *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 170–184, 2014.
- [32] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008, p. 60.
- [33] E. Hyttiä, H. Koskinen, P. E. Lassila, A. Penttinen, J. T. Virtamo, and J. Roszik, "Random waypoint model in wireless networks," 2005.

3.2 2. ekarpenarekin erlazionatutako artikuluak

3.2.1 Konferentzia-artikula (K3)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- E. Iradier, J. Montalban, L. Fanari, P. Angueira, O. Seijo and I. Val, "NOMA-based 802.11n for Broadcasting Multimedia Content in Factory Automation Environments," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Korea (South), 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971844.

Hona hemen artikulu honen kalitate-adierazle adierazgarriak:

- Argitalpen mota: IEEEExplore-n indexatutako konferentzia
- Saila: Konputazio zientziak eta ingeniaritza
- SJR faktorea: 0,300

NOMA-based 802.11n for Broadcasting Multimedia Content in Factory Automation Environments

E. Iradier, J. Montalban, L. Fanari, P. Angueira
Department of Communications Engineering
University of the Basque Country (UPV/EHU)
Plaza Torres Quevedo 1, Bilbao, Spain
{eneko.iradier, jon.montalban, pablo.angueira}@ehu.eus

O. Seijo, I. Val
Communication Systems Group
IK4-Ikerlan Technology Research Centre
Pº J.M. Arizmendiarieta 2, Mondragon, Spain
{oseijo, ival}@ikerlan.es

Abstract—Industry 4.0 requirements in reliability and latency are still a challenge for wireless communications systems due to the factory critical propagation scenarios. Additionally, further improvements are required in order to enhance the performance of wireless technologies in terms of reliability and latency before presenting them as a valid alternative to the wired technologies. These challenges are added to the increasing needs of bitrate to deliver multimedia content in Factory Automation (FA) environments. This paper proposes several use cases, which include video transmission and a specific technical solution based on a combination of NOMA and the IEEE 802.11n standard. The PHY/MAC proposal is evaluated on a reference scenario based on the deployment of the typical industrial applications. Results show that NOMA-based systems offer a very promising reliability gain in comparison to classical TDMA-based systems. In fact, for the most unbalanced service combinations a PER (Packet Error Rate) improvement of more than one order of magnitude can be obtained.

Keywords— 802.11, Broadcast, Factory Automation, Multicast, Multimedia Content, NOMA, Reliability.

I. INTRODUCTION

Multimedia content distribution and, specifically, video consumption will be one of the most relevant factors for the traffic increase in wireless networks in the coming years. According to the Cisco Visual Networking Index (VNI) Global Mobile Data Traffic Forecast Update [1], over three-fourths (78 percent) of the world's mobile data traffic will be video by 2021.

One of the novelties is that the environments where video is gaining momentum are not restricted to traditional video consumption and social networks. A new application area, which is rapidly developing and growing, is the industrial communications. Advanced communications in industry are one of the pillars of a process usually referred as the fourth industrial revolution (or Industry 4.0). This revolution consists of bringing all the benefits of the information and communications technologies (ICT) into the industrial sector in all its methods, tools and infrastructures. In consequence, this trend is expected to redesign the technical characteristics and even the philosophy of the industrial communications [2].

Communications in industry have been traditionally oriented to design control and alarm systems. In consequence, these systems have very strict temporal and reliability

requirements. What is more, usually they have been designed to transmit and receive very short and accurate amount of data. Nevertheless, the range of communication use cases in industry is widening and the delivery of video content may be needed sooner than expected [3]. In [4], how graphic and media technologies support operators in Industry 4.0 is presented.

Even if in principle they were not designed for deterministic and reliable communications, the 802.11 family of wireless standards is one of the most spread communication technologies in industry. There is a variety of reasons behind this success: the amount of available devices, the worldwide network deployments and the huge amount of applications that already have it implemented. Another key factor that make the difference between Wi-Fi and the rest of wireless connections (Bluetooth, NFC, LoRa...) is the use of Low Density Parity Check (LDPC) coding in the latest releases of the standard (802.11n and above), a more robust channel coding scheme in comparison with traditional convolutional codes. This improvement has turned 802.11n into a promising candidate for delivering critical information in factory automation environments.

In [5], authors present SHARP (Synchronous and Hybrid Architecture for Real-time Performance): a new communication system based on 802.11g for industrial automation. This design includes a modified 802.11g PHY layer and a deterministic Medium Access Control (MAC) based on Time Division Multiple Access (TDMA). This solution targets very challenging communication scenarios with strict time and reliability requirements. Therefore, determinism is almost guaranteed for critical services (CS), whereas the arrival of any other secondary communication service is not guaranteed.

The main contribution of the present paper is a solution that addresses the reliability requirements of the industry and the efficient transmission of multimedia contents. In particular, the use the Non-Orthogonal Multiple Access (NOMA) technique over the physical layer of the 802.11n standard is proposed. NOMA is a well-known technology that has been analyzed in combination with other technologies in different fields. Some of the most relevant examples of the success of NOMA are [6] and [7]. In [6], NOMA is presented as a candidate to be used in broadband mobile networks in

TABLE I. SUMMARY OF INDUSTRIAL USE CASES REQUIRING VIDEO TRANSMISSION

Use Case	ID	Critical Service: Reliability – Latency	Best Effort Service: Bitrate - Capacity
Remote Vehicle Guidance/Operation	1.A	Control/Telemetry data	Video Layer
	1.B	Core Video Layer (Scalable Video Coding)	Enhancement Video Layer (Scalable Video Coding)
Surveillance & Production Control Video Systems	2	Core Video Layer (Reliability, critical)	Enhancement Video Layer
Staff Safety in Industry: Augmented Reality and complementary Aid Systems	3.A	Workers Critical Telemetry Uplink: Bio indicators, position, sensors in hazardous production	Video Service (Uplink video from smart glasses, helmet camera, etc)
	3.B	Critical Warning / Safety Message Data	Augmented Reality Data
General Purpose Automation and Multimedia delivery	4	Automation Control Service	Multimedia Service (safety information to screens, panels, etc)
Advanced Imagery Systems	5.A	Robust Video: Target Tracking, Low Latency Video (low fps, 1 only)	Enhancement Video Layer: High Resolution thermographic video
	5.B	Control Data	Enhancement Video Layer: High Resolution thermographic video
Condition Monitoring Applications	6	Critical data depending on the application: Stress, temperature, turns per second, speed, etc.	Video monitoring of the application

combination with subgrouping techniques in order to improve the overall network capacity. In [7], a low complexity version of NOMA, Layered Division Multiplexing (LDM), is proposed for the next generation terrestrial broadcasting systems, especially focused on ATSC 3.0.

The main benefit of NOMA is that, under certain conditions, provides higher spectrum efficiency with respect to the classical orthogonal multiplexing techniques. Moreover, NOMA offers an interesting increase in flexibility, which means a wider range of possible transmission configurations. As a matter of fact, in the literature it has been demonstrated that using LDM it is possible to increase the reliability, the transmission capacity or even both simultaneously [8].

To our best knowledge, this paper offers a comprehensive analysis of a video broadcasting/multicasting system within an industrial environment and based on an 802.11n-NOMA physical layer.

The paper is organized as follows. Section II describes the characteristics and requirements of industrial communications and defines different use cases for broadcasting video. Section III provides a realistic application scenario and a particular PHY/MAC solution architecture. Then, Section IV describes the results of the system network performance, and finally, the conclusions are presented in Section V.

II. ENVIRONMENT OVERVIEW

In this section, the possible future ecosystem for wireless industrial communications is presented. Firstly, the tight requirements that must be fulfilled are shown, and secondly, the most relevant industrial use cases including video content are highlighted.

A. Factory Automation requirements

Factory Automation (FA) scenarios are considered one of the most challenging scenarios where industrial

communications have to be deployed. The FA concept is related to the complete production chains where the most important elements are mainly machines. These environments include Device-to-Device (D2D) communications and complete control systems, which require real-time control. Some FA examples are: assembly, packaging, palletizing and manufacturing industries.

These processes communications must be extremely robust, and thus, reliability becomes a critical factor. In addition, the latency value can be as critical as the reliability. In a recent work [9], the maximum affordable latency is considered between 0.25-10 ms, with an update time of 0.5-50 ms. What is more, the Packet Loss Rate (PLR) is also a tight requirement with a goal that can be as low as 10^{-9} (if retransmissions or some other reliability-increasing mechanisms are enabled). Finally, it must be noted that the typical coverage area for these communication systems is up to 50-100 meters.

B. Possible use cases

Apart from the strict requirements that control communications require, there is also a demand for delay and loss tolerant services. These flexible services are referred as Best Effort (BE) services and among other things, they can be related to the media delivery.

Taking into account the quick change that the industry is facing, it is time to consider multimedia content (especially, audiovisual contents) as a real candidate for the BE services. What is more, in some cases they might be considered for the critical services too. This service distinction leads to an interesting unbalance between the capacities of both services. As it has been proved in theory [8], the greater the unbalance, the higher is the achievable gain with non-orthogonal multiplexing techniques.

TABLE II. SERVICES CHARACTERISTICS

ID	Name	Description	Transmitter	Receiver	Transmission method	Critical/BE
S1	Network synchronization	Superframe starting signal, responsible for the synchronization of the nodes and emergency alarm.	AP	Every node	Broadcast	Critical
S2	Sensing instructions	Concrete parameters for configuring the sensing. If the packet is not received, sensing will be done with previous parameters.	AP	One slave per superframe	Unicast	BE
S3	UHD Video	Video content about the overall system performance.	AP	Both displays	Multicast	BE
S4	Sensed parameters	Basic results of the sensing process.	Slave receiving S2	AP	Unicast	Critical
S5	Video data	Video data of the sensing process. Complementary information.	Slave receiving S2	AP	Unicast	BE

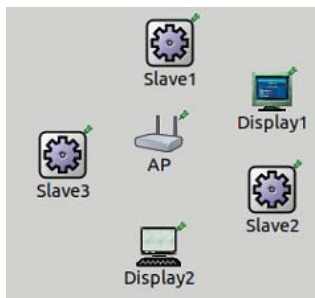


Fig 1. Simulated network in OMNeT++.

Taking this idea as a reference, a summary of different possible industrial use cases (1-6) is shown in TABLE I, where video broadcasting is considered as an enhanced service or even as a critical service. Moreover, for each use case, up to two different examples of critical and enhanced services have been proposed. Each of this use cases involves two services with different requirements: critical service (CS) and BE. Firstly, the critical service is loss and delay intolerant. On the one hand, CS are related with workers safety or with vital data communication for the application. On the other hand, BE services are less strict and so, they are considered loss and delay tolerant. Normally, they are related with supplementary application data, which does not interfere in the overall performance.

Regarding TABLE I, it is important to highlight that depending on the use case, video content can also be delivered as a critical service. For example, in use case 5 (Advanced Imagery Systems), which is a very promising field for surgery applications, a demand for critical video data can be assumed. In fact, a critical basic video is delivered in order to guarantee a pseudo-perfect communication, whereas a best effort video service is also offered for enhancing the video quality or adding some other features (thermography, humidity...).

III. PERFORMANCE EVALUATION SCENARIO

In order to study the performance of a NOMA-based 802.11n system for broadcasting multimedia content, a complete evaluation tool has been developed. In particular, in

TABLE III. AVAILABLE MCS VALUES IN THE 802.11N STANDARD

MCS	Modulation	Coderate	Capacity (Mbps)
0	BPSK	1/2	6
1	QPSK	1/2	12
2	QPSK	3/4	18
3	16-QAM	1/2	24
4	16-QAM	3/4	36
5	64-QAM	2/3	48
6	64-QAM	3/4	54
7	64-QAM	5/6	60

this paper, the work is based on the use case 6 from TABLE I. The evaluation performance is simulated in OMNeT++ [10].

A. General settings of the scenario

In this section, a generic monitoring application for an industrial indoor environment is presented. For that aim, a six-device network topology is included, where each node has a different role. The network is composed of an Access Point (AP), three sensing slaves and two displays. In Fig. 1, the simulated network over OMNeT++ is shown.

The AP node is the master node of the network. One of its main roles is the network synchronization. The AP also requests sensing information to each node in a superframe time span and distributes the video content that has to be delivered. The sensing slaves have also transceiver capacities. They are able to receive information from the AP, and send their sensed information (data and complementary video).

In TABLE II, a summary of the different offered network services is shown, including a service description as well as the target receivers. In this proposal, the unicast, multicast and broadcast services will share the same superframe structure. In the last column of TABLE II, each service is classified in terms of the loss tolerance level, and so, two categories are differentiated again: critical and BE. As critical services are related to loss intolerant services, they are transmitted with low Modulation and Code Scheme (MCS) value in order to obtain a higher reliability (see TABLE III). A network restriction has been imposed in order to guarantee a minimum quality: the overall critical service traffic must offer a minimum value of 6 Mbps. However, due to the philosophy of the BE services, this traffic is transmitted with higher MCS values to achieve high transmission rates.

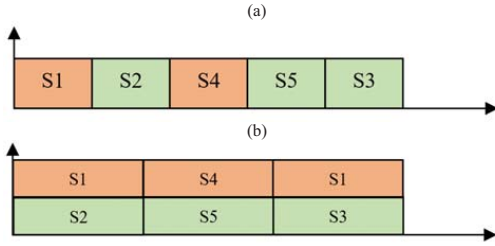


Fig 2. Time schedule representation: (a) TDMA-based, (b) NOMA-based

From the industrial communications requirements point of view, this communication system has to guarantee low latency and low update time values, especially for critical services. Hence, the length of the superframe has a constant value of 3 ms, and the slot size is modified depending on the number of slots, the multiplexing technology and the implemented MCS.

B. PHY/MAC level definition

The management of the medium access is a key factor for the deterministic communications, where reliability is considered a critical factor. Hence, as it is shown in Fig. 2, different time schedules have to be defined depending on the applied multiplexing technique.

Firstly, for the TDMA systems (Fig. 2.a), traffic categories are divided in different slots. A portion of the time is reserved for critical service (orange time slots), and the rest of the time for BE services (green time slots). For example, if each slot has the same time-length, the time division will be: 2/5 for critical services and 3/5 for BE services. That means that to achieve the minimum required value for the critical traffic, the lowest available MCS is number 2, QPSK 3/4, which offers 18 Mbps. The choice for the suitable MCS value for BE is a tradeoff between capacity and maximum allowable error rate.

In the case of the NOMA-based systems, traffic is multiplexed not only in the time domain, but also in the power domain (Fig. 2.b). Due to that, both traffic types can be offered the 100% of the time. Consequently, in this case, the lowest MCS value (BPSK 1/2) can be used without breaking the minimum required capacity. Moreover, for BE services any of the available MCS values can be used.

In order to implement this specific multiplexing scheme, the optimal injection level has to be defined. This parameter divides the overall transmitted power between the Core Layer (CL), which is reserved for Real-Time traffic, and Enhanced Layer (EL), which is used to deliver BE services.

IV. RESULTS AND DISCUSSION

In this section, the proposed technical solution is evaluated. First, the simulated cases and propagation scenarios are presented, and then, the obtained results are plotted and discussed.

A. Simulated scenarios

Several configurations have been designed including different parameters and multiplexing techniques. However, capacity constraints are common for both multiplexing

TABLE IV. CONFIGURATION PARAMETERS

Scenario parameter	
Service area	30x30, 50x50, 100x100
Fading model	NLOS Industrial Model
Path Loss coefficient	2.5
Transmitted power	10, 20 dBm
Rx noise threshold	90 dBm
Cycle time	3 ms
PHY/MAC parameter	
Critical service throughput	6 Mbps
BE throughput	24, 48 Mbps
TDMA configuration	Case A: 50% - 50% (MCS1-MCS5) Case B: 20% - 80% (MCS4-MCS7)
NOMA configuration	Case A: -2.5 dB (MCS0-MCS3) Case B: -1.5 dB (MCS0-MCS5)

techniques. In this work, 6 Mbps are assumed for critical services, which is enough capacity to offer critical service, and two different approaches have been proposed for BE services (Case A and Case B), 24 Mbps and 48 Mbps, respectively. Both of them can accommodate high quality multimedia content, even in UHD format.

First, in order to configure TDMA services, the time resources are shared between both services, and then, a suitable MCS value is chosen to achieve the expected minimum capacity value. Consequently, as it is shown in TABLE IV, in Case A, a 50% - 50% time division is set and the selected MCS values are MCS1 and MCS5, respectively. Additionally, in the second approach, in Case B, a 20% - 80% time division is fixed and the corresponding MCS values are MCS4 and MCS7, respectively.

Second, in the NOMA case the injection level value has been defined for each capacity combination (see TABLE IV) in order to multiplex the services in the power domain. For Case A, a -2.5 dB injection level has been applied, and for Case B, -1.5 dB. In addition, in the NOMA-based case, lower MCS values are selected because they are transmitted over the whole RF channel the 100% of the time.

Finally, the most relevant scenario parameters have been defined. Concerning the communication channel, an industrial channel model with Non-Line-Of-Sight (NLOS) condition and 29 ns rms delay spread [11] has been implemented. The path loss coefficient is set to 2.5 [12]. Moreover, three different service areas have been evaluated (30x30, 50x50 and 100x100) in order to broaden the study scenarios. In addition, transmitted packets airtime is set to 100 μ s. Therefore, each packet size varies depending on the MCS value. Eventually, two different transmission power has been tested 10 dBm and 20 dBm (this is the maximum allowed value for the ISM frequency bands in Europe) [13].

B. Results

Results are gathered based on the configurations described in the previous section (Fig 3 and Fig 4). What is more, two subplots are shown in each figure, one for each use case (Case A and Case B). Eventually, the following services are studied for each scenario: NOMA critical, NOMA BE, TDMA critical and TDMA BE. Regarding the plots, the vertical axis describes the PER value and the horizontal axis a certain scenario.

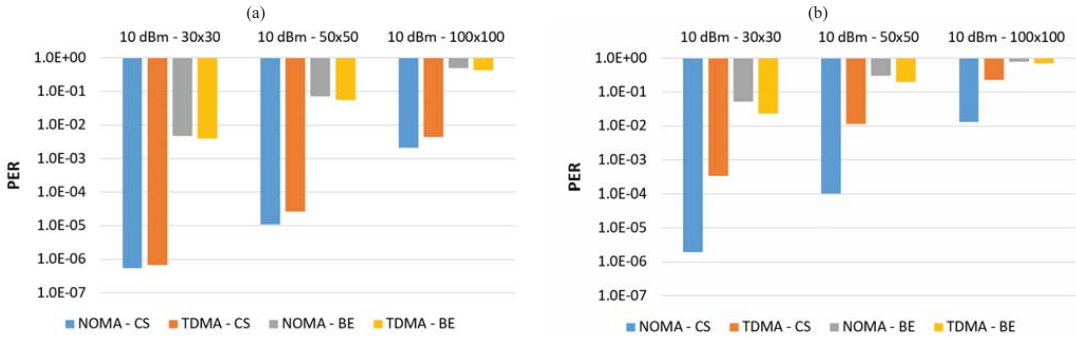


Fig 3. PER comparison for constant transmitted power: (a) Case A, (b) Case B

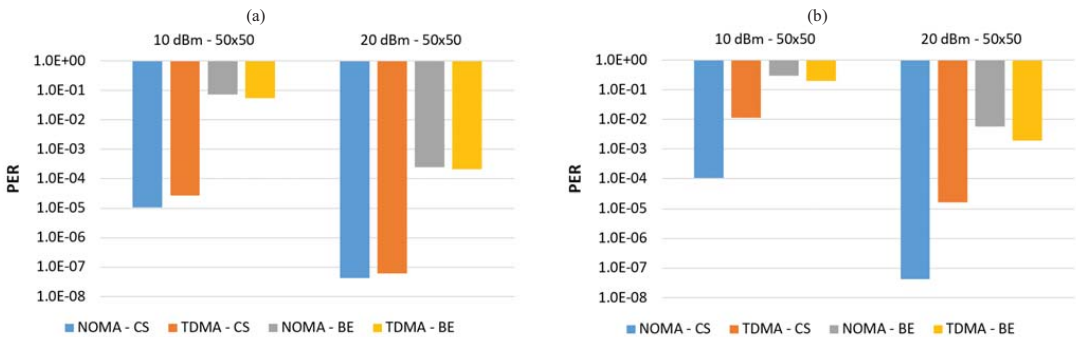


Fig 4. PER comparison for constant service area: (a) Case A, (b) Case B

In Fig 3, it is proven that as expected, the service area size is directly proportional to the obtained PER. The bigger is the factory size area, the higher are the path losses. Secondly, concerning Fig 4, it can be concluded that the transmitted power has just the opposite impact. Therefore, the higher the transmitted power, the lower the packet error values. Moreover, an in-depth analysis can be done involving the service area and the transmitted power. On the one hand, in the case of the smallest service area (30x30), implementable reliability values are obtained by transmitting 10 dBm, especially with NOMA. Consequently, for this case, it is not necessary to increase the transmitted power. On the other hand, the 50x50 case is more dependent on the applied MCS. Therefore, transmitting 10 dBm should be reserved only for very robust MCS values and the rest should be transmitted with a higher transmitted power. Finally, in the biggest service area case, the conclusion is obvious, 10 dBm is not enough power in order to guarantee a reliable service. Hence, using 10 dBm is rejected and higher transmitted power have to be implemented, preferably by using NOMA as the multiplexing technique.

On the other hand, analyzing the different services performance for each scenario it can be seen that although a little reliability loss is obtained for BE services in the NOMA case, a considerably big gain is obtained for critical services. This trend is maintained for both propagations scenarios. In

addition, it must be pointed out that the reliability is the key factor mostly for critical services, whereas in the case of BE services, reliability is not a priority, and consequently, a little degradation can be tolerated.

It is also remarkable that the reliability gain is very dependent of the implemented MCS case. In fact, the performance differences between NOMA (blue and orange bars) and TDMA (grey and yellow bars) for Case B (Fig 3.b and Fig 4.b) are higher than the ones obtained in Fig 3.a and Fig 4.a for Case A. The main reason lies in the NOMA information theory basis. As it is shown in [8], the bigger the unbalance between CL and EL capacities, the greater is the obtained gain in comparison with orthogonal techniques.

The maximum gain related to critical services in Case A is obtained in the 10 dBm and 50x50 scenario, where the PER value is reduced from $2.67 \cdot 10^{-5}$ to $1.08 \cdot 10^{-5}$. However, this gain is considerably improved in each of the evaluated configurations in Case B. Furthermore, using NOMA in Case B improves around two magnitude orders in almost each scenario. For instance, the minimum gain is obtained in 10 dBm and 100x100 scenario, where more than a magnitude order gain is obtained (from 0.226 to 0.013), whereas the maximum is obtained for the 20 dBm and 50x50 configuration, where NOMA-based reliability offers a gain close to three magnitude orders (from $1.63 \cdot 10^{-5}$ to $6.03 \cdot 10^{-8}$).

Finally, it is also important to highlight the performance of both multiplexing techniques in the most challenging scenario: Case B, 10 dBm and 100x100 (see Fig 3.b). By using TDMA, a PER value of 0.2 is obtained, whereas NOMA reliability is set close to 0.01. Although both values are quite high, the difference between them is critical. Taking into account that retransmissions are not included in the MAC layer, PER values can be easily improved in the medium access layer. Therefore, the reliability obtained in the worse performing scenario using NOMA could be used in some soft-real-time applications. However, the reliability value obtained with TDMA is not enough for this scenario and, hence, it has no possible application.

V. CONCLUSION

This paper presents a novel technical solution for including efficiently multimedia content delivery in industrial communications. In order to carry out this work, traditional TDMA multiplexing schemes and the more recent NOMA multiplexing schemes have been combined with the 802.11n standard. To test the performance a realistic scenario has been described and a specific MAC layer has been designed for each technology. The evaluation phase has been completed with different configurations of the common scenario, trying to prove the viability of the proposal in different challenging situations.

The results show that NOMA can be considered as a real candidate to distribute multimedia content within industrial environments due to its great simulation results. In fact, NOMA-based communications have overcome TDMA-based results in each of the scenarios for the critical services, which are the most reliability dependent services. Despite the little losses that are obtained for the BE services, the PER gain for the critical services would recommend its implementation. Actually, a reduction of two order of magnitude is achieved in several cases by implementing NOMA.

ACKNOWLEDGMENTS

This work has been partially supported by the Basque Government under the PREDOC grant program

(PRE_2018_1_0344) and by the Spanish Government under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE).

REFERENCES

- [1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021.
- [2] R. Drath and A. Horch, "Industrie 4.0: Hit or Hype? [Industry Forum]," in *IEEE Industrial Electronics Magazine*, vol. 8, no. 2, pp. 56-58, June 2014.
- [3] L. L. Bello, "Novel trends in automotive networks: A perspective on Ethernet and the IEEE Audio Video Bridging," *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*, Barcelona, 2014, pp. 1-8.
- [4] J. Posada et al., "Graphics and Media Technologies for Operators in Industry 4.0," in *IEEE Computer Graphics and Applications*, vol. 38, no. 5, pp. 119-132, Sep/Oct. 2018.
- [5] Ó. Seijo, Z. Fernández, I. Val and J. A. López-Fernández, "SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks," *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, Imperia, 2018, pp. 1-10.
- [6] J. Montalban et al., "Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 91-95, March 2018.
- [7] S. I. Park et al., "Low complexity layered division multiplexing system for the next generation terrestrial broadcasting," *2015 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*, Ghent, 2015, pp. 1-3.
- [8] L. Zhang et al., "Layered-Division-Multiplexing: Theory and Practice," in *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 216-232, March 2016.
- [9] P. Schulz et al., "Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture," in *IEEE Communications Magazine*, vol. 55, no. 2, pp. 70-78, February 2017.
- [10] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proc. 1st Simutools*, Brussels, Belgium, 2008.
- [11] F. Molisch et al., "IEEE 802.15. 4a channel model-final report," *IEEE P802*, vol. 15, no. 04, pp. 1-41, 2004.
- [12] J. Miranda et al., "Path loss exponent analysis in Wireless Sensor Networks: Experimental evaluation," *2013 11th IEEE International Conference on Industrial Informatics (INDIN)*, Bochum, 2013, pp. 54-58.
- [13] M. Luvisotto, Z. Pang and D. Dzung, "Ultra High Performance Wireless Control for Critical Applications: Challenges and Directions," in *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1448-1459, June 2017.

3.2.2 Aldizkari-artikulua (A4)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- J. Montalban, E. Iradier, P. Angueira, O. Seijo and I. Val, "NOMA-Based 802.11n for Industrial Automation," in IEEE Access, vol. 8, pp. 168546-168557, 2020, doi: 10.1109/ACCESS.2020.3023275.

Hona hemen artikulu honen kalitate-adierazle adierazgarriak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 61/266 (Q1) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,745

Received August 26, 2020, accepted September 8, 2020, date of publication September 10, 2020, date of current version September 24, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3023275

NOMA-Based 802.11n for Industrial Automation

JON MONTALBAN¹, (Member, IEEE), ENKO IRADIER¹, (Graduate Student Member, IEEE), PABLO ANGUIERA¹, (Senior Member, IEEE), OSCAR SEIJO², (Member, IEEE), AND IÑAKI VAL², (Senior Member, IEEE)

¹Department of Communications Engineering, University of the Basque Country (UPV/EHU), 48013 Bilbao, Spain
²IKERLAN Technology Research Centre, Basque Research and Technology Alliance (BRTA), 20500 Mondragón, Spain

Corresponding author: Eneko Iradier (eneko.iradier@ehu.es)

This work was supported in part by the Basque Government under Grant IT1234-19, in part by the PREDOC Grant Program under Grant PRE_2019_2_0037 and project U4INDUSTRY (ELKARTEK), and in part by the Spanish Government (Project PHANTOM) (MCIU/AEI/FEDER, UE) under Grant RTI2018-099162-B-I00.

ABSTRACT Industry 4.0 and Industrial Internet refer to the expected revolution in production, utility management and, in general, fully automated, interconnected and digitally managed industrial ecosystems. One of the key enablers for Industry 4.0 lies on reliable and timely exchange of information and large scale deployment of wireless communications in industry facilities. Wireless will bring solutions to overcome the main drawbacks of the current wired systems: lack of mobility, deployment costs, cable damage dependency and scalability. However, the strict requirements in reliability and latency of use cases such as Factory Automation (FA) and Process Automation (PA) are still a major challenge and a barrier for massive deployment of currently available wireless standards. This paper proposes a PHY/MAC wireless communication solution for FA and PA based on Non-Orthogonal Multiple Access (NOMA) in combination with the 802.11n standard. The communication system proposed aims at delivering two different sets of services. The first service class is composed of Critical Services (CS) with strict restrictions in reliability and latency. The same communication system should convey also a second group of services, referred as Best Effort (BE) with more relaxed boundary conditions. The proposal theoretical background, a detailed transmission-reception architecture, the physical layer performance and the MAC level system reliability are presented in this paper. The solution provides significantly better reliability and higher flexibility than TDMA systems, jointly with a predictable control-cycle latency.

INDEX TERMS 802.11, Factory Automation, IWSN, local area networks, NOMA, P-NOMA Process Automation.

I. INTRODUCTION

The fourth industrial revolution is driving the research and the development in the field of industrial communications. One of the expected trends is the progressive deployment of wireless interconnections as well as global automation for improving efficiency in the use of resources and the integration between processes and factories [1]–[4]. Even though, wired connections are still ruling the majority of the industrial environments. The main reason is the uncertainty of current wireless standards for guaranteeing the tight requirements posed by industrial use cases.

As a paradigmatic example, the 802.11 family of wireless standards was not designed for industrial communications. Nevertheless, they have emerged also as

a candidate for industrial applications because of their wide range of available devices, network deployments and applications in practically all communication fields. A major advantage of 802.11 relies on its similarity in OSI layer architecture and compatible protocol structure with Ethernet. This fact provides a high level of interoperability and ensures simple implementation of Ethernet/WLAN internetworking functions. On the weak side, its medium access mechanism, CSMA/CA, does not guarantee deterministic behavior. This fact is a major drawback for real-time services in networks where a massive number of nodes are potentially operating in a crowded spectrum environment [5]. In addition, the standard lacks efficiency for traffic profiles associated to industrial wireless communications (short packets) [6].

A typical Industrial Wireless Sensor Network (IWSN) is depicted in Fig. 1. A generic control system with specific performance and control cycle requirements is assumed.

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Pau¹.

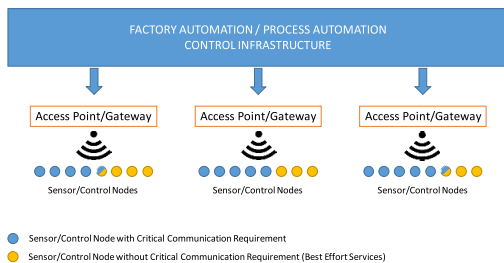


FIGURE 1. Typical industrial wireless sensor network in an industrial environment.

The control system has several access points/gateways (AP) that will serve a set of sensor/control nodes. The distinction of sensor and control functions will be associated to uplink and downlink capabilities of each node. There will be two types of nodes depending on the services associated. Some nodes will be linked to critical services (CS), with strict performance and latency restrictions. Others will not present tight restrictions and will be served on a best effort (BE) basis. Moreover, nodes receiving CS traffic could also be BE receivers. Additionally and in line with performance/latency restrictions, CS and BE service throughput requirements will also be different. In consequence, it is expected that the wireless connection will carry services with orthogonal requirements.

This unbalanced traffic scenario is the perfect operating point for Non-Orthogonal Multiple Access (NOMA) techniques and especially for Layered Division Multiplexing (LDM) [7], a specific power domain NOMA (P-NOMA). LDM has proven better reliability and throughput than the traditional TDM/FDM resource allocation schemes [8]. There are already preliminary proposals in literature for applying NOMA to industrial communications. In [9], authors calculate the robustness and capacity of an ideal NOMA system based on Shannon capacity. However, this work does not provide a complete architecture description in combination with existing standards (PHY and MAC layers) and does not consider specific modulation and coding schemes (MCS), neither provides the combined performance of a PHY and MAC layer. Then in [10], a cross-layer is design to be used between the physical and the data link layers to enhance the energy efficiency in downlink NOMA wireless networks for Visible Light Communication (VLC). Nevertheless, the analysis is carried out adapting the coding and the modulation without considering the integration in any standard and the reliability performance is not studied. In [11], a NOMA-based 802.11n PHY approach is presented and tested in some scenarios. However, no MAC layer is used to provide a realistic industrial communication and the results presented do not reach the low Packet Error Rate (PER) values required the industry.

Aiming at flexibility, capacity and reliability in wireless industrial applications, the present paper proposes the joint

use of NOMA/LDM and 802.11n. Although this paper proposes a viability analysis using the well-established 802.11n standard, this proposal will be applicable for future versions, such as 802.11ax and 802.11be. The technical contributions of this paper include:

1. To our best knowledge, this paper is the first comprehensive system design and analysis of a NOMA-based 802.11n architecture for industrial communications. A fully detailed explanation of the transmitter and receiver chains is provided, and in addition, the modification that have been assumed in order to make it compatible with the current 802.11n are also included.
2. The proposal gathers also for the first time, in a single framework, the principal steps that any technology has to overcome during the first phase of the standardization process: theoretical background and evaluation, design of the architecture, computer based simulations at PHY and MAC level and network evaluation.
3. A specific MAC layer superframe schedule is designed and evaluated to cope with the specifications of a NOMA-based service delivery.
4. The evaluation of each Key Performance Indicator (KPI) has been carried out according to strict conditions close to real applications. In particular, extensive simulations have been run in order to obtain PER values up to 10^{-3} on the physical layer and 10^{-9} at MAC level. The main reason for this demanding evaluation is to facilitate the possible know-how transfer to industry in the near future.

The paper is organized as follows. The next section describes the characteristics and requirements of industrial communications, as well as the description of two typical industrial scenarios. Section III provides an overview of the system proposal based on 802.11n and NOMA. Section IV discusses necessary modifications in the PHY in order to use NOMA with the 802.11n and the proposal is evaluated in terms of reliability. Section V introduces a deterministic MAC layer based on Time Division Multiple Access (TDMA) to evaluate the PHY proposal in combination with retransmission techniques. Then, in section VI the PHY/MAC proposal is tested in a realistic use case describing the system network performance. Finally, Section VII contains the main conclusions.

II. INDUSTRIAL COMMUNICATION TECHNOLOGIES AND REQUIREMENTS

This section presents the main wireless solutions for industrial communications and the possible use cases.

A. WIRELESS TECHNOLOGIES

According to available literature, such as [12], 802.11 and 802.15 are the most common building blocks in proposals for wireless industrial communications.

802.15 is a working group inside the IEEE 802 specialized in Wireless Personal Area Networks (WPAN) [13]. 802.15 standards are focused on low energy, low-range,

low-data rate, and multi-hop topologies; thus, they are a suitable family for building industrial wireless sensor networks. In addition, the standard supports a deterministic access scheme that provides a bounded latency [14]. However, their usability is commonly limited to monitoring applications due to their low data rate, modest PER, and relatively large latencies [15]. Some wireless networks for industry process monitoring have been effectively implemented using 802.15.4. For instance, [16] presents an 802.15.4-based network for predictive maintenance of manufacturing installations and railway transport. In [16], the authors point out that 802.15.4 can hardly be applied for strict control or safety applications for latency and reliability concerns. Some other works try to improve the feasibility of 802.15.4 for control applications. In [17], a wireless network build with 802.15.4 and a custom TDMA MAC is presented. The TDMA MAC optimizes the network delays and minimizes the cycle time. However, the minimum achievable cycle time was in the 10 ms order, which is out of several industrial applications [18], [19] and they do not mention the achieved PER.

802.11 has been also considered for industrial communication applications. Compared to the 802.15 family, 802.11 provides higher throughput and range. In 2009, the IEEE standardization committees released the standard version IEEE 802.11n [20], which offers up to five times faster transmission modes in comparison with its predecessor, especially due to the introduction of Multiple-Input Multiple-Output (MIMO) systems [21]. Authors in [6] have tested it on real-time industrial communications and the outcome has been a set of guidelines and recommendations in terms of reliability and latency. However, reliability values are only presented up to PER values of 10^{-1} , which is far away from typical industrial performance requirements and it is not realistic to extrapolate those values to very low PER values taking into account the high variance of the industrial wireless propagation channels. Recently, cross layer approaches are a matter of discussion, not only from a PHY-MAC point of view, but also from the network layer perspective. In [22], authors detail different key design aspects in ultra-high-performance wireless networks for critical industrial control applications but unfortunately no simulations results were included. Finally, in [23], SHARP (Synchronous and Hybrid Architecture for Real-time Performance) is presented, a new architecture for industrial automation. Its wireless part includes a novel PHY layer based on 802.11g and integrated in a TDMA MAC structure in order to guarantee deterministic behavior. In this case, convolutional codes are used as channel coding, which are far away from the reliability performance of the LDPC codes introduced in 802.11n.

In summary, the solutions presented so far do not meet the strict industrial requirements and although the 802.11 standard family seems to be more prepared to be integrated in the industry, it cannot be still considered the optimum technology.

B. USE CASES AND SCENARIOS

This paper addresses two industrial communication application use cases: Factory Automation (FA) and Process Automation (PA).

FA refers to industrial communication environments where either individual machines or complete systems require real-time control. These cases are related to production chains, where machines are fundamental elements of the process. Some representative examples would be assembly, packaging, palletizing and manufacturing. Due to the critical role of communications in their respective processes, depending on the application, they require bounded latencies (0.25-10 ms) and Packet Loss Rate (PLR) in the range of 10^{-7} - 10^{-9} . In addition, the update time is between 0.5-50 ms and coverage areas are usually well below 100 meters [24], [25].

PA refers to industrial communications for monitoring and diagnosing applications. Examples of PA typical fields are heating, cooling, stirring, and pumping procedures and, in general, machinery condition monitoring. A major difference with FA is the variation speed of measurements and control cycle latency requirements. Most representative values of latency and reliability are within the ranges of 50-100 ms and 10^{-3} - 10^{-4} packet loss rate, respectively. Moreover, an update time of 0.1-5 seconds is usually required. Communication ranges are larger than in FA and may vary between 100 and 500 meters [24], [25].

In this work, two deployment scenarios are proposed for system evaluation purposes. In both cases, two services are expected: one critical service (CS), and one non-critical service that will be referred as best effort (BE) service. On the one hand, both PA and FA services will be regarded as critical (CS) even though their requirements in terms of latency and reliability will be different. On the other hand, BE services will not have latency and reliability restrictions and will be applicable in any scenario and use case.

The scenarios provide boundary conditions such as number of nodes, bitrate allocated to each service, service area dimensions and propagation channel characteristics. Scenarios and associated parameters have been based on reference models and experimental data available in [26] and [27] and are gathered in TABLE 1. On the one hand, scenario A represents a relatively large manufacturing hall, with 3200 sq. meters (80×40 m). We assume up to 100 nodes randomly distributed throughout the hall. The access point/gateway will be installed in an optimal position, where LOS and partially obstructed Fresnel zone conditions dominate. On the other hand, Scenario B represents a manufacturing cell, with limited dimensions (10×10 m), up to 20 nodes per cell and NLOS reception conditions. In both cases, a typical manufacturing environment is emulated with plenty of metallic structures and moving machines and staff. The propagation channel (CM 7 or CM 8) choice associated to each environment has been based on [28] and the experiments carried

out on [26]. TABLE 1 summarizes the main parameters and values of each case.

TABLE 1. Use cases and application scenarios.

Parameter	Scenario A Manufacturing Hall	Scenario B Manufacturing Cell
Application	PA	FA
Dimensions (m)	80 x 40 x 10	10 x 10 x 10
Number of Nodes	Up to 100	Up to 20
Critical Services (Mbps)	24	12
Non - Critical Services (Mbps)	Up to 48	Up to 48
Channel Model (IEEE 802.15.4)	CM7	CM8

The service capacity requirements associated to the critical services have been differentiated in each scenario. Scenario A has higher number of nodes and lower PER requirement, whereas Scenario B presents less nodes, lower distances and requires a very low PER. Consequently, we have chosen a bitrate capacity close to 24 Mbps for the critical service, whereas this number is reduced to 12 Mbps for the manufacturing cell in scenario B. In both cases, the target throughput of the BE services is 48 Mbps.

III. NOMA-BASED 802.11n

This section introduces the basic principles of NOMA and the requirements for its integration within the 802.11n standard.

A. NON-ORTHOGONAL MULTIPLE ACCESS (NOMA)

Power domain NOMA has recently been successfully applied to broadcast communications [29]. P-NOMA is very efficient in providing different levels of robustness to different services within the same RF channel. This makes the technology an adequate candidate for multiplexing services with unbalanced requirements in industrial wireless applications.

NOMA consists of a signal ensemble composed of several layers, each one taking a portion of the total power delivered by the transmitter. Each layer is configured targeting different robustness levels, decoding thresholds and capacities. The configuration is a function of the modulation/coding choice and the power assignment to each layer. The power splitting is described by Δ (injection level, measured in decibels). The concept of multiplexing two services with NOMA is illustrated in Fig. 2 and the NOMA signal ensemble can be expressed as:

$$x_{NOMA}(k) = x_{CS}(k) + g \cdot x_{BE}(k), \quad (1)$$

where $x_{CS}(k)$ and $x_{BE}(k)$ are the two data streams combined into $x_{NOMA}(k)$ and k is the subchannel index. The injection level g defines the linear power allocation ratio between layers in linear units [7]. This work is based on a two-layer system and, therefore, layers are referred as Upper Layer (UL) and Lower Layer (LL), where CS is transmitted in the UL and BE in the LL, as described in Fig. 2. Due to the power splitting, each service is delivered with less power than in the single-layer case and the power allocated to each

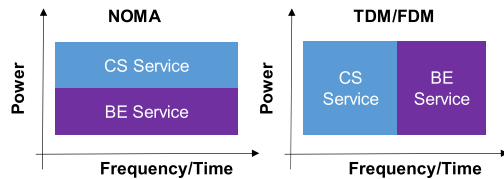


FIGURE 2. Non-Orthogonal and Orthogonal Multiplexing (OM) schemes sharing both the time and the frequency resources.

service can be calculated as:

$$\sigma_i = \frac{10^{\frac{\Delta_{i-1}}{10}}}{\sum_{i=1}^N 10^{\frac{\Delta_{i-1}}{10}}}, \quad (2)$$

where, σ_i is the power allocation ratio for layer i (i.e., $i = 1, 2$), N is the total number of layers in the signal ensemble (i.e., $N = 2$) and Δ is the injection level in dB.

The idea of multiple signals on the same channel with unequal error protection was described time ago by some information theory papers such as [30]. The currently available advances in forward error correction make NOMA feasible in real systems. The performance of latest LDPC codes, for instance, is less than half a dB away from the Shannon limit [31]. The second driver for feasibility is the implementation of the signal cancellation structure proposed in [6], which reduces significantly the complexity of the receiver [32]. In [6], a comprehensive comparison of the spectral efficiency of NOMA and traditional TDM/FDM schemes was presented. It is proven that provided the service reception thresholds are unbalanced, the overall gain offered by NOMA can be up to 3 bps/Hz. In practice this gain can be invested in two benefits: 30% higher throughput compared to TDMA solutions [33], [34] or a considerable PER reduction [35]. NOMA will always outperform TDM/FDM, provided an efficient enough channel coding mechanism is used.

Industrial communication systems are typically rolled out for supervision and control purposes, where security, reliability and delay will be critical design constraints. NOMA addresses both security and reliability directly by operating close to zero and even with negative reception thresholds for the most challenging scenarios. Flexible configuration of layers is also an advantage for increasing the security of the PHY. Moreover, processing time and complexity at the receiver are key for system feasibility in industrial environments. The cancellation associated to additional layer decoding involves additional processing latency on the receiver. However, the CS is not affected by this inconvenience as it is transmitted in the UL. Even though, the selected error coding technique for the physical layer waveform will be very important for the Successive Interference Cancellation (SIC) delay [36]. In [32], for instance, the latency associated to large LDPC codes was analyzed. The results show that the number of iterations of the LDPC decoding algorithm remains lower than 5 for Signal-to-Noise Ratio (SNR) values below 4-5 dB,

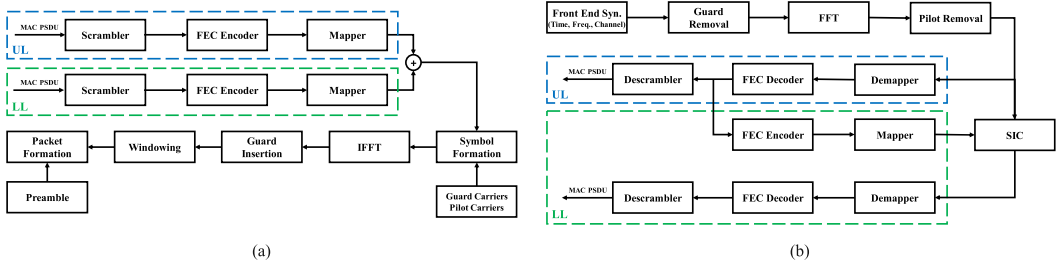


FIGURE 3. General block diagram of the proposed transceiver: (a) NOMA-based 802.11n transmitter, (b) NOMA-based 802.11n receiver.

making the associated decoding time not relevant on the overall OFDM receiver processing time budget, mostly influenced by MAC operations [32]. It should be noted that time requirements cannot be described on a general basis. Each application scenario requires a thorough analysis of the control-cycle vs. receiver processing time.

B. NOMA ON 802.11n

A new communication architecture based on modifications to the PHY of the 802.11n standard in order to include NOMA is presented in this subsection.

First, at the MAC layer, the LL Physical Service Data Unit (PSDU) packet length is adjusted according to the UL length in order to ensure that both components, UL and LL, will make use of the same number of symbols per frame in the physical layer. This adaptation will enable the use of a simplified NOMA mapping block, which will be included immediately after the combination of individual mappers plus an amplitude adaptation operation (injection level). Consequently, the LL receiver complexity will be greatly reduced. Previous work already assessed the relevancy of a proper choice of the data overlapping for efficient and simple receiver implementation [32]. In particular, the length of the BE PSDU can be calculated as:

$$PSDU_{BE} = \lfloor (Sym_{Num(CS)} * NDBPS_{BE} - N_{Service}) / 8 \rfloor \quad (3)$$

where, $Sym_{Num(CS)}$ is the number of complex symbols required for the CS, $NDBPS_{BE}$ is the number of coded bits per OFDM symbol of the BE service and $N_{Service}$ is the number of bits in the service field.

In fact, if the system uses OFDM and the framing structure of each one of the layers are synchronized, the receiver complexity and latency are limited. The mapping and framing stage are inherited directly from 802.11n MCS. The only difference is that both services are combined into a single stream after mapping (see Fig. 3 (a)). To do so, the complex symbols corresponding to the LL are attenuated by a predefined injection level. The injection level in linear units (i.e., g) indicates the relative power distribution between both layers, so g has a real value within the range $[0, 1)$, where $g = 0$ results in a single-layer system and $g = 1$ results

in a two-layer system with equal power distribution. Then, the UL and the attenuated LL are added creating the definitive NOMA signal ensemble. After superimposing both layers, the output constellation is normalized. In this particular case, the UL is in charge of delivering CS content, while BE content is mapped into the LL. Once both services are combined into a single P-NOMA signal ensemble, both services will undergo the same processing stages. The final physical waveform is then sent in the form of PHY packets composed of a preamble and a data field. The detailed structure of the PHY packet is maintained as defined in 802.11n.

The first modules of the NOMA receiver are identical to those on current 802.11n receivers (See Fig. 3 (b)). After RF conditioning, the carrier and time synch stages prepare the input for channel and equivalent noise estimation.

Then a Least Square (LS)-based equalization is performed and the CS goes through decoding, demapping and descrambling stages. The CS bit stream will be available for all sensor/actuators of the service area without additional complexity since the lower layer will be assumed as additional noise for the UL. If the available SNR permits, the cancellation and lower layer decoding will be the next steps. The cancellation will depend on the injection level, the channel estimation metrics and the CS itself. At the receiver, the NOMA ensemble on the k -th channel can be expressed as:

$$y_{NOMA}(k) = (x_{CS}(k) + g \cdot x_{BE}(k)) \cdot h(k) + n(k), \quad (4)$$

where $y_{NOMA}(k)$ is the received symbol, $h(k)$ is a static multipath channel and $n(k)$ is the sum of AWGN noise and other additive interference. CS can be accessed as usual without any further requirements. Once the UL has been decoded, a signal cancellation algorithm provides access to the BE. In this work, for the signal cancellation stage the Hard-SIC cancellation scheme is proposed due to its good trade-off between complexity and performance. In particular, the same Hard-SIC cancellation mechanism has been adopted by receivers of latest Advanced Television Systems Committee (ATSC) digital TV standard, ATSC 3.0, showing a successful balance between complexity and performance [29]. The decoded CS layer is coded and modulated again, and then, it is removed from the equalized NOMA signal

(See Fig. 3 (b)). After these stages, the received signal can be expressed as:

$$\tilde{x}_{BE}(k) = g \cdot x_{BE}(k) + i(k) + n(k), \quad (5)$$

where $i(k)$ is the error cancellation due to the channel estimation error and \tilde{x}_{BE} is the obtained BE data [6]. Eventually, the obtained signal goes through the same decoding, demapping and descrambling stages as the CS.

C. CAPACITY COMPARISON

The purpose of this section is to demonstrate theoretically that the inclusion of NOMA in 802.11n standard provides an increase of the system capacity. Fig. 4 shows the capacity gain of NOMA for different configurations. The x-axis represents the percentage of time dedicated to the delivery of CS content, while the y-axis is the capacity gain obtained as the difference between the optimum TDM configuration throughput and the optimum NOMA throughput. The different curves imply different restriction on the maximum SNR value that CS and BE services can assume. Based on those values the optimum MCS configuration is carried out for both technologies.

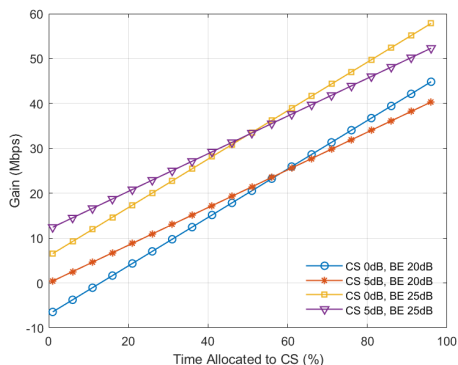


FIGURE 4. Potential gain using NOMA in combination with 802.11n.

Firstly, Fig. 4 shows that in the majority of the cases, NOMA offers a considerable capacity gain with maximum values between 40-60 Mbps. The gain increases linearly proportional to the percentage of time allocated to CS, where the higher are the time requirements of CS, the higher is the gain that NOMA can offer. In addition, the curves present different gradient due to the performance of NOMA. In fact, the higher is the asymmetry between the SNR requirements of the services, the higher is the gradient of the gain that NOMA can offer. Finally, it should also be remarked that for the low values of time percentage allocated to CS, NOMA does not provide enough gain, and so, TDM could be a better solution. However, taking into account the industrial time requirements, cases where the majority of the time are allocated to non-critical services are not very representative. The main reason is that service configuration is carried out

to meet the strict requirements of CS and, therefore, a low percentage of time dedicated to CS may indicate that the service configuration is not optimized.

D. PROPOSED CONFIGURATIONS

Based on the scenarios described in previous sections, two different configurations are proposed for each of the multiplexing schemes. On the one hand, in the NOMA-Config. A (PA), the UL is targeting a CS with a throughput of about 24 Mbps (MCS1), whereas the LL is delivering 48 Mbps (MCS3) as a BE service and the injection level is -10.5 dB. In NOMA-Config. B (FA), the UL is decreased to 12 Mbps (MCS0) and the injection level to -10 dB in order to satisfy the more tight requirements of FA, while the EL configuration remains the same. PHY configurations are summarized in TABLE 2.

TABLE 2. PHY configurations.

		NOMA	TDM
PA - Scenario A	Config. A	QPSK 1/2	16 QAM 1/2
	CS (24 Mbps)	16QAM 1/2	64QAM 2/3
	BE (48 Mbps)		
FA - Scenario B	Config. B	BPSK 1/2	QPSK 1/2
	CS (12 Mbps)	16QAM 1/2	64QAM 2/3
	BE (48 Mbps)		

On the other hand, the resources are always 50%-50% shared by both service types in TDM/FDM configurations. In the first case, TDM-Config. A, the MCS3 is proposed for the CS, whereas for the second scenario TDM-Config. B the MCS1 is enough to satisfy the minimum CS throughput. Eventually, in both cases the BE data is conveyed with MCS5 and a throughput of 48 Mbps. The packet length of the CS service has been configured to deliver a payload of 18 bytes.

IV. PHYSICAL LAYER (PHY)

This section provides guidelines for the design of the proposed PHY layer and presents the performance analysis.

A. DESIGN

The potential gain of the NOMA proposal has been studied by through simulations of the complete physical layer [37], [38]. A prototype transmitter and receiver chain has been implemented for this purpose. This prototype is compliant with the 802.11 a/g/n standard and includes modifications to enable NOMA multiplexing capabilities as described in Section III (See Fig. 3).

The system evaluation set up has included two industrial propagation models for performance evaluation purposes: the CM 7 (Scenario A) and CM 8 (Scenario B) channel models [28]. Considering this work as a feasibility analysis of the upper limit of the potential gain provided by NOMA to 802.11n, perfect synchronization and channel estimation are assumed. Access the Lower Layer is granted after SIC cancellation as explained in Section III.B. In line with the ideal

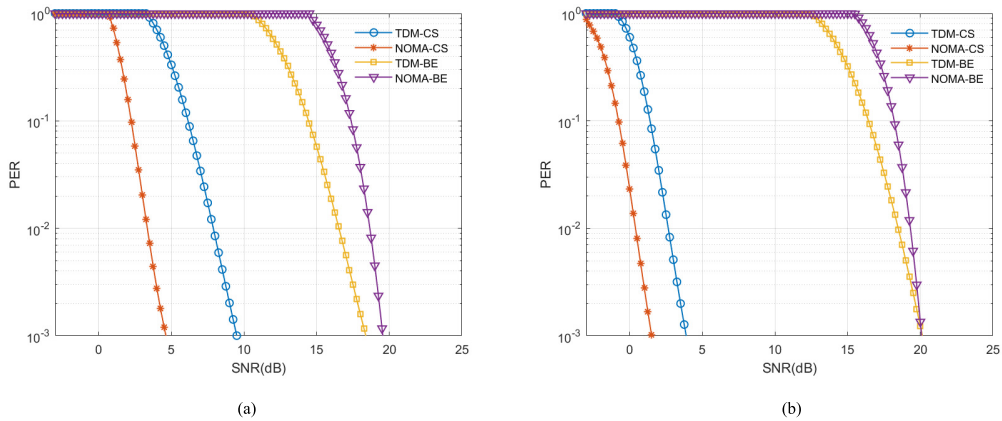


FIGURE 5. Performance results for the PHY layer: (a) Scenario A (b) Scenario B.

synch and estimation considerations, cancellation has been also considered ideal. Previous works have demonstrated that it is possible to keep the cancellation noise below the system AWGN [7], [39].

The PHY performance has been evaluated using. This is one of the key performance indicators in industrial applications (a PSDU packet is considered erroneous if any of the bits are decoded incorrectly). The number of simulated packets and the SNR simulation steps have been adapted to the expected PER values. In particular, the simulated packet number is always at least one order of magnitude higher than the required value for obtaining the desired PER value assuming one single error. In addition, for the best granularity the lower PER values are calculated within 0.25 dB steps. The obtained results are fed to OMNeT++ as the PHY error model.

B. EVALUATION

As part of the proposal study, the PHY performance of configurations proposed in Section III.D are displayed in Fig. 5 (a) and Fig. 5 (b) for Scenario A and Scenario B, respectively. The receiving thresholds at the physical layer are limited to $\text{PER} = 10^{-3}$. It must be noted, that the MAC level retransmissions, even limited for latency considerations, will bring PER values down to 10^{-8} .

The UL gain in Fig. 5 (a) is close to 5 dB, whereas the LL performance is within a 1.5 dB margin for both multiplexing schemes. In Fig. 5 (b), however, the NOMA UL gain is reduced to about 2.5 dB and the LL performance is even closer. The relevance of the result lies on the significant gain in PHY performance, close to 5 dB gain for a very challenging scenario, which will provide room for flexible MAC design. The reason for this gain is that in order to compensate the capacity reduction in TDMA systems because of the resource sharing between CS and BE, higher modulation orders have

to be used in comparison with NOMA. Therefore, more robust configurations can be used in NOMA, while the same capacity as in TDMA is offered.

V. MAC LAYER DEFINITION AND PERFORMANCE

This section presents the design of the proposed MAC layer and the performance analysis.

A. DESIGN

In this section, a specific MAC layer for implementing the NOMA-based 802.11n PHY proposal is presented. This MAC layer proposal combines in the same time schedule the NOMA signal ensemble with a TDMA medium access technique to guarantee deterministic packet delivery and a packet retransmission scheme in the time domain to increase the reliability. Additionally, it is assumed that the nodes share a common time reference that allows guaranteed access to the medium without any interferences, such as [40], [41]. In order to measure the benefits of introducing NOMA, a single-layer TDMA MAC with packet retransmission schemes has been designed and implemented. Both MAC layer superframe structures, TDMA and NOMA + TDMA, are presented in Fig. 6.

Both superframe structures are composed of four different periods: CS transmission, uplink feedback, on-demand retransmissions and BE period. During the CS transmission period, the AP sends the corresponding CS information to each slave in a dedicated time slot. Then, in the uplink feedback period, each slave sends an ACK packet if the CS has been correctly received or NACK packet if the CS has not been correctly received. The ACK/NACK packet transmission is carried out in single-layer mode in both cases, TDMA and NOMA. In the on-demand retransmission period, each of the requested retransmissions in the previous period is carried out by the AP in another dedicated time slot. To define

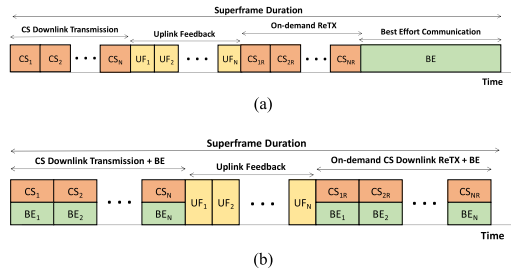


FIGURE 6. Superframe time representation: (a) TDMA, (b) NOMA + TDMA.

the duration of this period, the worst possible case is assumed, that is, one slot per each CS packet retransmission is reserved. Finally, in the BE period non-critical information is delivered. The length of each period depends on the MCS on use. The lower the MCS is, the higher the required transmission time is, and so, the longer the period is. Taking into account the PHY configurations (TABLE 2), since NOMA uses lower MCS values, NOMA periods are longer than TDMA periods for the same packet lengths.

The main difference between the two superframe structures is that by using NOMA, BE services are delivered in the LL. On the one hand, this effect reduces the superframe time duration since only three periods have to be reserved in the time domain. On the other hand, as NOMA techniques are implemented in combination with a deterministic TDMA structure, BE services are transmitted in the lower layer aligned with CS. In consequence, it will be much easier to determine the timing of the transmission and the reception of each BE packet since the determinism obtained by the use of TDMA is also applied to the BE services. The consequence is an easier prediction of latency also for BE services. Another advantage of the simultaneous delivery of CS and BE services is that when a retransmissions are required for CS, the BE packet is also retransmitted, and so, a second chance is obtained for the correct reception of BE traffic.

B. EVALUATION

In order to evaluate the reliability of the proposed MAC layer, the OMNeT++ network simulator has been used [42]. The designed MAC layer has been implemented in combination with the PHY configurations described in the previous section. The scenarios (A and B) described in section II.B have been used (see TABLE 1). The number of nodes in the network has been set initially to 50 in scenario A and 10 in scenario B. Later, the impact of increasing the number of nodes and the maximum slots of a TDM/NOMA superframe as a function of T_{Cycle} will be calculated.

Firstly, the superframe length is different for each technology and configuration. Therefore, the minimum T_{Cycle} would also be different, since in this work, the T_{Cycle} is assumed as the minimum required time to carry out all the required communications described in the superframe

(i.e., the superframe length), which means that the lower the T_{Cycle} , the faster are the slaves updated. In particular, for the same number of nodes, NOMA superframes are shorter than TDM superframes. In fact, TDM superframe is 22% and 17.5% longer than NOMA superframe in scenario A and scenario B, respectively.

In Fig. 7, CS reliability curves obtained from the MAC evaluation are presented in terms of PER and PLR vs. SNR. This work assumes PER as the error rate without retransmissions and PLR as the error rate after implementing retransmissions. Regarding the performance obtained in scenario A (Fig. 7 (a)), NOMA-based MAC offers better results than TDM for restrictive PER and PLR values (i.e., 10^{-9}). In particular, NOMA performs 2.5 dB better than TDM in terms of PLR and more than 6 dB in terms of PER.

If the impact of the retransmission schemes is individually analyzed, the relative reliability improvement achieved in TDM is higher than in NOMA (i.e., 7dB vs. 4 dB). The difference on the impact of the retransmissions is associated to PHY configurations in each case, as TDM uses a less robust MCS, retransmissions are more effective. Similar reliability results are obtained in Fig. 7 (b) for scenario B. In this case, the gain that NOMA-based system offers in comparison with TDM system is 2.3 dB and 1.7 dB in terms of PLR and PER, respectively. In general, performance values are better in scenario B since more robust configurations are implemented for the CS.

The PER performance of the BE component is presented in Fig. 8. In the case of scenario B, performance results are very similar in both cases, the difference is lower than half dB. However, in scenario A TDM offers slightly higher reliability (around 3 dB). Nevertheless, the reliability difference for both technologies is not as critical as in the case of CS. Moreover, PLR results of the NOMA MAC layer are not included in Fig. 8 since they are very similar to the PER values. The main reason for this effect is the short time interval between the transmission and the retransmission, usually much shorter than channel time coherence.

VI. COMPREHENSIVE NETWORK EVALUATION

In this section, the PHY layer (Section IV) and the MAC (Section V) are combined based on the scenarios detailed in Section II.B. The objective of this study is to test the proposed solution in terms of reliability and latency in a realistic network. Simulations have been carried out in OMNeT++. The system uses a 40 MHz channel bandwidth in the 2.4 GHz ISM band, -90dBm is the thermal noise power and the transmitted power is set to 10 dBm. It is assumed that the nodes are randomly distributed along the network. The path loss model includes the free space path losses plus a shadowing component that is characterized with a log-normal distribution with mean zero and $\sigma = 6\text{ dB}$ [43]. A summary of the parameters is presented in TABLE 3.

Fig. 9 shows the results of reliability associated to each scenario. Scenario A and Scenario B are presented independently in Fig. 9 (a) and Fig. 9 (b), respectively. In general,

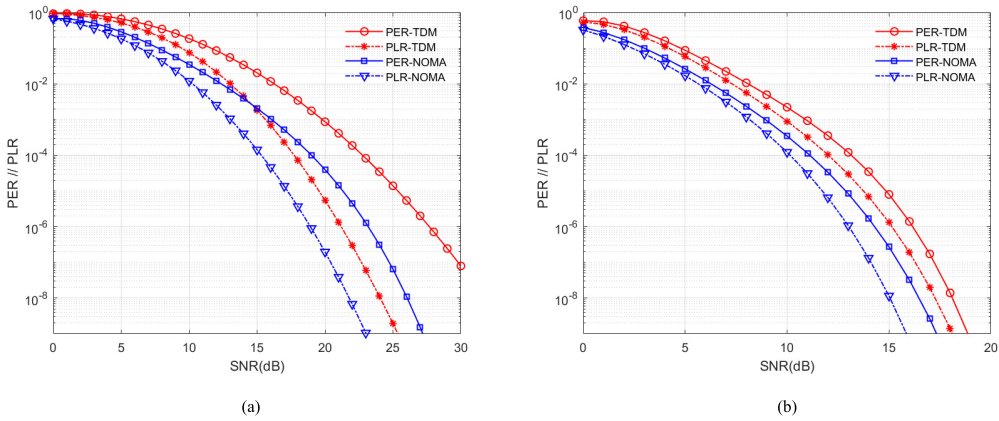


FIGURE 7. MAC layer CS reliability results: (a) Scenario A, (b) Scenario B.

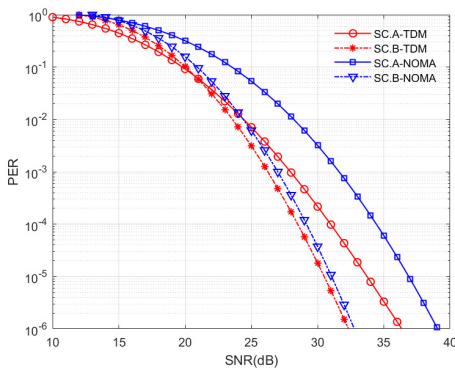


FIGURE 8. MAC layer BE reliability results.

TABLE 3. Simulation parameters.

Parameter	Value
Center Frequency	2.4 GHz
Bandwidth	40 MHz
Noise Power	-90 dBm
Transmitted Power	10 dBm
Shadowing	Mean = 0 dB $\sigma = 6$ dB
Number of Nodes	50 in Sc. A 10 in Sc. B
Channel Model	CM7 in Sc. A CM8 in Sc. B
Network Size	80 x 40 m ² in Sc. A 10 x 10 m ² in Sc. B
CS data rate	24 Mbps in Sc. A 12 Mbps in Sc. B
BE data rate	48 Mbps

NOMA offers considerable better performance for the CS. In fact, in all CS cases (see Fig. 9), NOMA outperforms TDM in at least one order of magnitude. In particular,

PLR values below 10^{-8} are obtained using NOMA. On the other hand, looking at BE services, TDM offers slightly better performance results than NOMA in Scenario A, while in Scenario B, results are very similar for both technologies. In addition, to the reliability results, the effect of the error packets and the retransmissions over the received throughput is presented in TABLE 4. As in the case of reliability results, NOMA provides a better use of system data capacity for CS services as results appear closer to the maximum (i.e., 24 Mbps in scenario A and 12 Mbps in scenario B) results. On the contrary, regarding the received effective throughput related with BE services, TDM-based architecture provides slightly better results, although, in both cases, the throughput decrease is assumable taking into account the characteristics of BE services. In summary, in order to improve the reliability of CS by using NOMA, a tradeoff has to be assumed between the performance of the CS and the BE.

Concerning time requirements, an end-to-end (E2E) latency analysis is presented in TABLE 5. NOMA can assume lower T_{Cycle} values while carrying out the same services as in TDMA. Then, the minimum E2E latency is defined as the time required to deliver a CS data packet. As expected, the minimum latency of NOMA is higher than the minimum latency of TDM because it uses lower MCS in the PHY configuration. The maximum latency is obtained when the CS packet is received in the on-demand retransmission period. Again, the different MCS choices cause different maximum values. Finally, the last column in TABLE 5, presents the mean latency obtained from the simulation of all the scenarios. In general, mean values are very close to the minimum latency values in all cases. This means that few retransmissions have been required to deliver the CS information correctly. However, the difference between the minimum and the mean latency is lower in NOMA than in TDM, because of its higher reliability. Doubtlessly, results

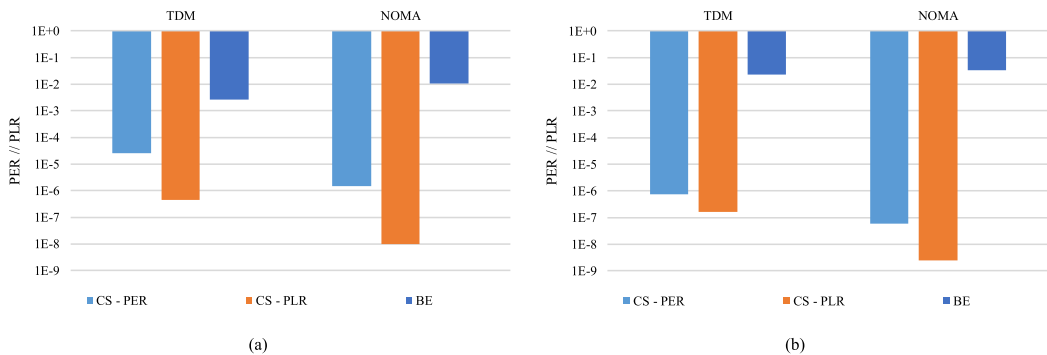


FIGURE 9. Reliability results obtained in: (a) Scenario A, (b) Scenario B.

TABLE 4. Received effective throughput.

	CS (Mbps)	BE (Mbps)
Sc. A - TDM	23.999401	47.869998
Sc. A - NOMA	23.999965	47.478968
Sc. B - TDM	11.999991	46.875871
Sc. B - NOMA	11.999999	46.349872

TABLE 5. E2E latency comparison.

	T_{cycle} (ms)	Min. E2E Latency (μs)	Max. E2E Latency (ms)	Mean E2E Latency (μs)
Sc. A - TDM	10.4	50	5.20	50.13000
Sc. A - NOMA	8.50	58	5.60	58.00500
Sc. B - TDM	2.28	58	1.12	58.00100
Sc. B - NOMA	1.94	70	1.24	70.00003

indicate that NOMA-based systems are more deterministic than TDM systems, since instantaneous latency values are less variable.

The length of the superframe structure is conditioned by the number of nodes that are served in each cycle time. Therefore, depending on the time requirements that have to be guaranteed (maximum cycle time), different number of nodes can be served depending on the multiplexing technology used. TABLE 6 contains the number of nodes that can be included in the designed superframe for different T_{cycle} values. The first two values (100 ms and 50 ms) are related to PA environments, where time requirements are more flexible. Then, the other three values (10 ms, 5 ms and 1 ms) are related to FA environments. In general, by using NOMA, more nodes can be included, specifically, the amount of served nodes can be increased by around 20%. It is worth mentioning the case of a T_{cycle} of 100 ms, where the number of nodes in the superframe is maximum. In this case, by using NOMA 108 extra nodes could be served in scenario A and 77 more in scenario B.

Finally, it is important to highlight that although originally only scenario B is oriented to FA environments (scenario A is oriented to PA), based on the latency and

TABLE 6. Served nodes for different T_{cycle} sizes.

	100 ms	T_{cycle} 50 ms	10 ms	5 ms	1 ms
Sc. A - TDM	480	240	48	24	4
Sc. A - NOMA	588	294	58	29	5
Sc. B - TDM	438	219	43	21	4
Sc. B - NOMA	515	257	51	25	5

reliability results obtained in TABLE 5 and Fig. 9, in both scenarios FA applications could be delivered by using NOMA.

VII. CONCLUSION

This article provides a comprehensive proposal of a NOMA-based 802.11n architecture for industrial applications. In addition to the necessary theoretical basis and the specific PHY/MAC NOMA design in combination with 802.11n, realistic requirements and scenarios have been detailed based on PA and FA, where the NOMA-based 802.11n proposal could be implemented. First, a simulation setup has been presented at PHY level in order to test the reliability increase obtained by introducing NOMA in the PHY. Then, a particular MAC layer structure has been presented to manage a deterministic medium access with a useful retransmission scheme. Finally, the performance of the PHY/MAC design has been tested in the described industrial scenarios. Reliability and latency have been the principal KPI.

In general, NOMA offers significantly better reliability results than TDMA. On the one hand, as shown in Section IV, the reliability of the CS is highly increased by using more robust MCS configurations. On the other hand, the robustness increase in the NOMA-based CS is maintained in the MAC layer performance curves. In fact, up to 6 dB of gain can be obtained for PER values of 10^{-9} , since NOMA-based CS can be obtained for a SNR of around 27 dB, while for TDMA around 33 dB of SNR are required. In addition, the effect of the proposed time retransmission scheme is confirmed in both technologies NOMA and TDM, since the required SNR is reduced. It has been observed that in some cases, TDMA-based systems offer slightly better results for BE services, but this fact has not been considered critical for FA or PA scenarios. It is also important to emphasize that

in all the simulated realizations in section VI, an important improvement is obtained PER and PLR metrics for NOMA. In fact, NOMA-based results outperform TDM results in at least one order of magnitude in each of the evaluated cases. In both scenarios, the PLR value obtained by using NOMA is below 10^{-8} . Consequently, a tradeoff has to be assumed between CS and BE, where in order to obtain a considerable gain in the CS, BE services have to assume a little penalization.

Concerning latency analysis, results are more similar between both technologies than in the case of reliability. As presented in section VI, although it is true that minimum and maximum latency values are slightly lower in TDM system, in both cases latency values meet the FA time requirements. However, the mean latency results in NOMA are very close to the minimum latency, which means that the instantaneous latency values are more constant. This effect occurs due to the increase in reliability in NOMA cases and it implies that NOMA-based communications are more deterministic than TDMA-based communications. Moreover, it is important to highlight that due to the superframe structure, more nodes can be included in the NOMA-based superframe than in the TDMA-based superframe for the same T_{cycle} .

Finally, an extra advantage is obtained with NOMA in comparison to TDMA: determinism in BE services. In most cases, absolute latency values are not critical for BE services, but in our proposal, latency of BE services becomes more easily predictable than in TDMA frame structures. Finally, as a future work, it would be interesting to validate this proposal in an industrial environment with real hardware. Hence, how to implement this proposal in commercial devices would be studied for creating compatible transceivers with NOMA technology.

REFERENCES

- [1] A. Varghese and D. Tander, "Wireless requirements and challenges in industry 4.0," in *Proc. Int. Conf. Contemp. Comput. Informat. (IC3I)*, Mysore, India, Nov. 2014, pp. 634–638.
- [2] R. Drath and A. Horch, "Industrie 4.0: hit or hype? [Industry Forum]," *IEEE Ind. Electron. Mag.*, vol. 8, no. 2, pp. 56–58, Jun. 2014.
- [3] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, "Cyber-physical systems: The next computing revolution," in *Proc. Design Automat. Conf.*, Anaheim, CA, USA, Jun. 2010, pp. 731–736.
- [4] M. Annunziata and P. C. Evans, "Industrial Internet: Pushing the boundaries of minds and machine," in *General Electric*. General Electric Reports, 2012.
- [5] Z. Fernandez, C. Cruces, I. Val, and M. Mendicute, "Deterministic real-time access point concepts for industrial hybrid Ethernet/IEEE 802.11 networks," in *Proc. IEEE Int. Workshop Electron., Control, Meas., Signals Appl. Mechatronics (ECMSM)*, Donostia-San Sebastian, Spain, May 2017, pp. 1–6.
- [6] F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella, "On the use of IEEE 802.11n for industrial communications," *IEEE Trans. Ind. Informat.*, vol. 12, no. 5, pp. 1877–1886, Oct. 2016.
- [7] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H. M. Kim, J.-Y. Lee, P. Angueira, and J. Montalban, "Layered-Division-multiplexing: Theory and practice," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 216–232, Mar. 2016.
- [8] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-S. Kwak, "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 721–742, 2nd Quart., 2017.
- [9] E. Arruti, M. Mendicute, and M. Barrenechea, "Unequal error protection with LDM in inside carriage wireless communications," in *Proc. 15th Int. Conf. ITS Telecommun. (ITST)*, Warsaw, Poland, May 2017, pp. 1–5.
- [10] S. Murugaveni and K. Mahalakshmi, "A novel approach for non-orthogonal multiple access for delay sensitive industrial IoT communications for smart autonomous factories," *J. Ambient Intell. Humanized Comput.*, to be published.
- [11] E. Iradier, J. Montalban, L. Fanari, P. Angueira, O. Seijo, and I. Val, "NOMA-based 802.11n for broadcasting multimedia content in factory automation environments," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jeju, South Korea, Jun. 2019, pp. 1–6.
- [12] A. Frotzsch, U. Wetzker, M. Bauer, M. Rentschler, M. Beyer, S. Elspass, and H. Klessig, "Requirements and current solutions of wireless communication in industrial automation," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 67–72.
- [13] M. Bal, "Industrial applications of collaborative wireless sensor networks: A survey," in *Proc. IEEE 23rd Int. Symp. Ind. Electron. (ISIE)*, Istanbul, Turkey, Jun. 2014, pp. 1463–1468.
- [14] G. Cena, A. Valenzano, and S. Vitturi, "Hybrid wired/wireless networks for real-time communications," *IEEE Ind. Electron. Mag.*, vol. 2, no. 1, pp. 8–20, Mar. 2008.
- [15] V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4258–4265, Oct. 2009.
- [16] K. Das, P. Zand, and P. Havinga, "Industrial wireless monitoring with energy-harvesting devices," *IEEE Internet Comput.*, vol. 21, no. 1, pp. 12–20, Jan. 2017.
- [17] M. Anwar, Y. Xia, and Y. Zhan, "TDMA-based IEEE 802.15.4 for low-latency deterministic control applications," *IEEE Trans. Ind. Informat.*, vol. 12, no. 1, pp. 338–347, Feb. 2016.
- [18] M. Luvisotto, Z. Pang, and D. Dzung, "High-performance wireless networks for industrial control applications: New targets and feasibility," *Proc. IEEE*, vol. 107, no. 6, pp. 1074–1093, Jun. 2019.
- [19] G. J. Sutton, J. Zeng, R. P. Liu, W. Ni, D. N. Nguyen, B. A. Jayawickrama, X. Huang, M. Abolhasan, Z. Zhang, E. Dutkiewicz, and T. Lv, "Enabling technologies for ultra-reliable and low latency communications: From PHY and MAC layer perspectives," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2488–2524, 3rd Quart., 2019.
- [20] *Orthogonal Frequency Division Multiplexing (OFDM) PHY Specification, de Standard—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Nueva York, Estados Unidos, IEEE Computer Society, Standard 802.11, 2012, pp. 1583–1630.
- [21] J. Lorincz and D. Begusic, "Physical layer analysis of emerging IEEE 802.11n WLAN standard," in *Proc. 8th Int. Conf. Adv. Commun. Technol.*, Phoenix Park, South Korea, Feb. 2006, p. 194.
- [22] M. Luvisotto, Z. Pang, and D. Dzung, "Ultra high performance wireless control for critical applications: Challenges and directions," *IEEE Trans. Ind. Informat.*, vol. 13, no. 3, pp. 1448–1459, Jun. 2017.
- [23] O. Seijo, Z. Fernandez, I. Val, and J. A. Lopez-Fernandez, "SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks," in *Proc. 14th IEEE Int. Workshop Factory Commun. Syst. (WFCS)*, Imperia, Italy, Jun. 2018, pp. 1–10.
- [24] P. Schulz, M. Matthe, H. Klessig, M. Simsek, G. Fettweis, J. Ansari, S. A. Ashraf, B. Almeroth, J. Voigt, I. Riedel, A. Puschmann, A. Mitschele-Thiel, M. Müller, T. Elste, and M. Windisch, "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 70–78, Feb. 2017.
- [25] S. Dietrich, G. May, O. Wetter, H. Heeren, and G. Fohler, "Performance indicators and use case analysis for wireless networks in factory automation," in *Proc. 22nd IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Limassol, Cyprus, Sep. 2017, pp. 1–8.
- [26] R. Croonenbroeck, L. Underberg, A. Wulf, and R. Kays, "Measurements for the development of an enhanced model for wireless channels in industrial environments," in *Proc. IEEE 13th Int. Conf. Wireless Mobile Comput., New. Commun. (WiMob)*, Rome, Italy, Oct. 2017, pp. 1–8.
- [27] X. Jiang, Z. Pang, M. Luvisotto, F. Pan, R. Candell, and C. Fischione, "Using a large data set to improve industrial wireless communications: Latency, reliability, and security," *IEEE Ind. Electron. Mag.*, vol. 13, no. 1, pp. 6–12, Mar. 2019.
- [28] A. F. Molisch, *IEEE 802.15.4a Channel Model-Final Report*, IEEE Standard P802, vol. 15, no. 4, pp. 1–41, 2004.

- [29] S. I. Park, J.-Y. Lee, S. Myoung, L. Zhang, Y. Wu, J. Montalban, S. Kwon, B.-M. Lim, P. Angueira, H. M. Kim, N. Hur, and J. Kim, "Low complexity layered division multiplexing for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 233–243, Mar. 2016.
- [30] P. Bergmans and T. Cover, "Cooperative broadcasting," *IEEE Trans. Inf. Theory*, vol. 20, no. 3, pp. 317–324, May 1974.
- [31] L. Michael and D. Gomez-Barquero, "Bit-interleaved coded modulation (BICM) for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 181–188, Mar. 2016.
- [32] S. I. Park, Y. Wu, L. Zhang, J. Montalban, J.-Y. Lee, P. Angueira, S. Kwon, H. M. Kim, N. Hur, and J. Kim, "Low complexity layered division multiplexing system for the next generation terrestrial broadcasting," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2015, pp. 1–3.
- [33] S.-I. Park, J.-Y. Lee, B.-M. Lim, S. Kwon, J.-H. Seo, H. M. Kim, N. Hur, and J. Kim, "Field comparison tests of LDM and TDM in ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 64, no. 3, pp. 637–647, Sep. 2018.
- [34] J. Montalban, P. Scopelliti, M. Fadda, E. Iradier, C. Desogus, P. Angueira, M. Murrioni, and G. Araniti, "Multimedia multicast services in 5G networks: Subgrouping and non-orthogonal multiple access techniques," *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 91–95, Mar. 2018.
- [35] E. Iradier, J. Montalban, L. Fanari, P. Angueira, L. Zhang, Y. Wu, and W. Li, "Using NOMA for enabling Broadcast/Unicast convergence in 5G networks," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 503–514, Jun. 2020.
- [36] M. Zhan, Z. Pang, D. Dzung, and M. Xiao, "Channel coding for high performance wireless control in critical applications: Survey and analysis," *IEEE Access*, vol. 6, pp. 29648–29664, 2018.
- [37] F. Qin, X. Dai, and J. E. Mitchell, "Effective-SNR estimation for wireless sensor network using Kalman filter," *Ad Hoc Netw.*, vol. 11, no. 3, pp. 944–958, May 2013.
- [38] A. A. Kumar, K. Ovsthus, and L. M. Kristensen, "An industrial perspective on wireless sensor networks—A survey of requirements, protocols, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1391–1412, 3rd Quart., 2014.
- [39] L. Zhang, Y. Wu, W. Li, H. M. Kim, S.-I. Park, P. Angueira, J. Montalban, and M. Velez, "Application of DFT-based channel estimation for accurate signal cancellation in cloud-txn multi-layer broadcasting system," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Beijing, China, Jun. 2014, pp. 1–6.
- [40] A. Mahmood, R. Exel, H. Trsek, and T. Sauter, "Clock synchronization over IEEE 802.11—A survey of methodologies and protocols," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 907–922, Apr. 2017.
- [41] O. Seijo, J. A. Lopez-Fernandez, H.-P. Bernhard, and I. Val, "Enhanced time-stamping method for subnanosecond time synchronization in IEEE 802.11 over WLAN standard conditions," *IEEE Trans. Ind. Informat.*, vol. 16, no. 9, pp. 5792–5805, Sep. 2020.
- [42] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proc. 1st Int. ICST Conf. Simulation Tools Techn. Commun. New. Syst.*, 2008, p. 60.
- [43] D. A. Wassie, I. Rodriguez, G. Berardinelli, F. M. L. Tavares, T. B. Sorensen, and P. Mogensen, "Radio propagation analysis of industrial scenarios within the context of ultra-reliable communication," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Porto, Portugal, Jun. 2018, pp. 1–6.



JON MONTALBAN (Member, IEEE) received the M.S. and Ph.D. degrees in telecommunications engineering from the University of the Basque Country, Spain, in 2009 and 2014, respectively. He is part of the TSR (Radiocommunications and Signal Processing) research group at the University of the Basque Country, where he is currently an Assistant Professor, involved in several research projects. He has held visiting research appointments with Communication Research Centre (CRC), Canada, and Dublin City University (DCU), Ireland. His current research interests include the area of wireless communications and signal processing for reliable industrial communications. He was a co-recipient of several best paper awards, including the Scott Helt Memorial Award to recognize the best paper published in the IEEE TRANSACTIONS ON BROADCASTING, in 2019. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications, and he currently serves as an Associate Editor for IEEE ACCESS.



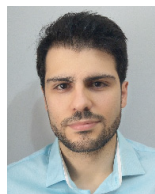
ENEKO IRADIER (Graduate Student Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of the Basque Country (UPV/EHU), in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree. Since 2015, he has been a part of the TSR Research Group, UPV/EHU. He was a Researcher with the Communications Systems Group, IK4-IKERLAN, from 2017 to 2018. During his Ph.D. studies, he did an internship with Communications Research Centre Canada, Ottawa. His current research interests include the design and development of new technologies for the physical layer of communication systems and wireless solutions for Industry 4.0. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications.



PABLO ANGUEIRA (Senior Member, IEEE) received the M.S. and Ph.D. degrees in telecommunication engineering from the University of the Basque Country, Spain, in 1997 and 2002, respectively.

He joined the Communications Engineering Department, University of the Basque Country, in 1998, where he is currently a Full Professor. He is part of the Staff of the Signal Processing and Radiocommunication Lab, where he has been involved in research on digital broadcasting (DVB-T, DRM, T-DAB, DVB-T2, DVB-NGH, and ATSC 3.0) for more than 20 years. He is coauthor of an extensive list of papers in international peer-reviewed journals, and a large number of conference presentations in digital broadcasting. He has also coauthored several contributions to the ITU-R working groups WP6 and WP3. His main research interests include the design and development of new technologies for the physical layer of communication systems in industrial wireless environments.

Dr. Angueira is a member of the IEEE BMSB International Steering Committee, an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, and a Distinguished Lecturer of the IEEE BTS. He serves on the Administrative Committee of the IEEE BTS.



OSCAR SEIJO (Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of Oviedo, Spain, in 2015 and 2017, respectively. He is currently pursuing the Ph.D. degree with the Communications Systems Group, IKERLAN Technological Research Centre, Mondragón, Spain, in collaboration with the Signal Theory and Communications (TSC) Group, University of Oviedo, Spain. His research interests include wireless high-performance PHY and MAC design for industrial applications, time synchronization over wireless systems, and digital signal processing.



IÑAKI VAL (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from the Department of Electronics Engineering, University of Mondragón, Spain, in 1998 and 2001, respectively, and the Ph.D. degree from the Department of Signals, Systems, and Radiocommunication, Polytechnic University of Madrid, Spain, in 2011. Since 2001, he has been with the Communications Systems Group, IKERLAN, Mondragón, Spain. He has been with Fraunhofer IIS of Erlangen, Germany, as an Invited Researcher, from 2005 to 2006. He is currently a Team Leader of the Communication Systems Group. His research interests include the design and implementation of digital wireless communications systems, industrial real-time requirements, communications for distributed control systems, vehicular communications, time synchronization, wireless channel characterization, and digital signal processing. He is currently focused on industrial communication applications.

3.2.3 Konferentzia-artikula (K4)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengo da:

- E. Iradier, J. Montalban, L. Fanari and P. Angueira, "On the Use of Spatial Diversity under Highly Challenging Channels for Ultra Reliable Communications," 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain, 2019, pp. 200-207, doi: 10.1109/ETFA.2019.8869055.

Hona hemen artikulua honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore-n indextatutako konferentzia
- Saila: Konputazio zientziak eta ingeniari-tza
- SJR faktorea: 0,365

On the Use of Spatial Diversity under Highly Challenging Channels for Ultra Reliable Communications

E. Iradier, J. Montalban, L. Fanari, P. Angueira
Department of Communication Engineering
University of the Basque Country (UPV/EHU)
Plaza Torres Quevedo 1, Bilbao, Spain

{eneko.iradier, jon.montalban, lorenzo.fanari, pablo.angueira}@ehu.es

Abstract— The Industry 4.0 concept is the result of latest technical advances that have completely changed the existing industrial vision, not only from the mechanical point of view, but also from the Machine-to-Machine (M2M) communication perspective. This revolution encompasses wireless communication technologies that are expected to be the replacement for traditional wired and fixed communication systems. However, industrial propagation channels are still a challenge for wireless industrial network deployments. This paper addresses this problem by proposing spatial diversity based retransmissions. Two general retransmission schemes have been tested: default and smart. Moreover, specific time scheduling choices have been proposed. The impact of the number of transmitters in relation to communication reliability has been analyzed. Results show that the use of spatial diversity based retransmissions makes restrictive reliability values feasible under realistic conditions. In fact, in the case of smart retransmissions, adding a second transmitter the reliability increases around 8 dB. Moreover, whereas the channel coherence time is a critical parameter for time based retransmissions, in the case of spatial diversity, the reliability performance has no dependency on the channel coherence time.

Keywords— 802.11, communications, factory automation, industry 4.0, PER, reliability, retransmissions, spatial diversity

I. INTRODUCTION

Industrial communications are radically changing the landscape of traditional industry. The introduction of networking and smart devices has led to the fourth industrial revolution, or Industry 4.0 [1]. One of the main challenges is the deployment of wireless network systems able to replace the traditional wired networks. In fact, wireless systems must guarantee the same performance as wired systems within the strictest industrial environments. In [2], the main requirements for Factory Automation (FA) use cases are listed. Certain reliability and latency values can be taken as goal values: 10^{-9} and 0.25-10 ms, respectively. Up to now, wired communication systems provide much better performance indicators. Nevertheless, applications that require mobility and complex deployments would benefit from wireless standard deployments.

A major challenge of current wireless communication systems is the simultaneous improvement of both, reliability and latency.

One of the most extended communication technologies for industrial wireless applications is the 802.11 standard family. Moreover, in 2009, the IEEE standardization committees released the standard IEEE 802.11n version, as an improvement of the existing 802.11g version. Authors in [3] tested for the first time the 802.11n standard for real-time industrial communications and provided a set of recommendations for reliability and latency enhancement. Furthermore, in the very recent literature, two interesting proposals should be highlighted: one providing guidelines for ultra-high-performance wireless networks and the other one proposing modifications to the 802.11g PHY/MAC (Physical Level/Medium Access Control) standard for industrial automation.

First, authors in [4] presented an overview of the different relevant characteristics that have to be taken into account in ultra-high-performance wireless networks for critical industrial control applications.

Second, in [5], SHARP (Synchronous and Hybrid Architecture for Real-time Performance) was presented, which is a novel proposal for wireless industrial automation networks. It included a modification of the 802.11g standard PHY/MAC levels and the determinism is introduced by using a TDMA access control scheme.

Industrial wireless channels present deep fading occurrences. SHARP and similar approaches compensate deep fades with high operation margins, and consequently, high Received Signal Strength Indicator (RSSI) values. The performance of these solutions in lower RSSI values is still a challenge.

Consequently, the difficulties in the physical propagation channel maintain wireless communications at a disadvantage in comparison with other wired communication systems. The reduction of the channel impact on system performance is necessary for real industrial deployments.

Current wireless communication standards, like the 802.11 family [6], are based on a cross-layer design. Typically, they standardized the PHY and the MAC levels. In this way, robust PHY layers can be designed, which allow the reception of frames with low Signal-to-Noise Ratio (SNR), and the overall performance can be improved by adding techniques for increasing the reliability in the MAC layer.

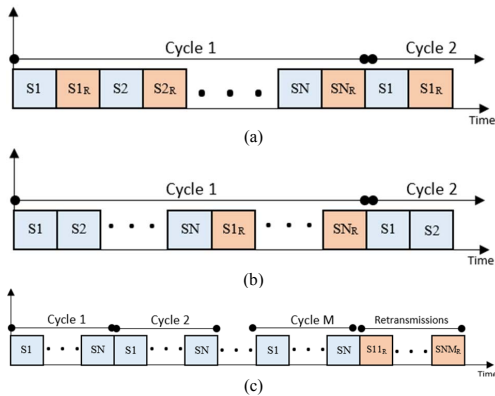


Fig 1. Retransmission schemes: (a) intra-slot, (b) intra-superframe, (c) superframe aggregation

In this line, a widely extended technique to reduce the amount of lost packets is the use of retransmissions. However, this technique is not always efficient in communications that need to guarantee low cycle times. If the reception of a packet fails due to eventual fading, it is highly probable that the retransmission slot fails again, because the link has not had enough time to recover.

In consequence, the main objective of this paper is to present spatial diversity as a mechanism for increasing the reliability and enhancing the communication success of 802.11 industry deployments. Different diversity schemes are presented here in order to avoid the wireless channel fading effect. For each presented scheme, the performance is evaluated in terms of reliability. Some guidelines obtained from the simulations are presented in order to facilitate the implementation of diversity based schemes and to guarantee its success.

The paper is organized as follows. The next section describes some theoretical work that have been done involving different mechanisms for increasing reliability. Section III provides the definition of the evaluating s . Section IV presents the simulation methodology that has been followed in this work. Then, Section V discusses the results obtained by applying a capacity constraint and Section VI shows the upper reliability bound results when none capacity constraint is applied. Section VII contains the future work and, finally, conclusions are highlighted in Section VIII.

II. MECHANISMS FOR INCREASING RELIABILITY

One of the modules in charge of measuring and guaranteeing robustness for a specific technology is the PHY layer. However, it should not attract all the attention; other techniques have to be introduced in order to obtain a meaningful performance. Many of these techniques are located either in the MAC level or managed at MAC and implemented in the PHY.

Retransmissions are a classical solution implemented in a wide variety of communication systems [7]. Their main drawback is efficiency, which generally is conditioned by the propagation channel characteristics. The channel coherence time is specifically a performance downgrading factor. Depending on the system requirements and the service characteristics, retransmissions can be scheduled in the time domain following diverse criteria. If the design is oriented to control systems, where low latency is needed, retransmissions will be carried out in the same time slot (intra-slot), as it is depicted in Fig 1.a, where retransmissions are represented by the letter R inside orange blocks. As it is designed in [5], retransmissions can also be delivered intra-superframe. In this case, different periods for transmissions and retransmissions are defined inside the superframe (see Fig 1.b). Finally, and especially for non-critical applications, where latency is not a restriction, retransmissions could be considered in groups of superframes (see Fig 1.c). Hence, it should be highlighted that before implementing retransmissions a tradeoff has to be assumed between reliability and latency.

In conclusion, alternative techniques have to be taken into account, in order to reduce the channel condition dependence. A simple but effective technique is spatial diversity. This technique consists of using more than one transmitting point to create several link options between the end device and the network, reducing the probability of a packet loss. Authors in [8] introduce spatial diversity in industrial communications and discuss potential applications. The main conclusion of this work is that it identifies the spatial diversity as a technical solution for next generation wireless industrial systems. However, authors do not provide any measurement to quantify the potential gain that could be achieved by using spatial diversity in comparison with time domain retransmissions. In addition, the use of relay nodes is developed in [9], another form of spatial diversity. For a given source, destination and wireless channel, authors evaluate the position of the relay node together with the most suitable retransmission strategy: retransmissions on demand or after error packet detection.

Wi-Red, Wi-Fi Redundancy, is another interesting approach for industrial reliable wireless communications [10]. Wi-Red aims at providing seamless link-level redundancy in IEEE 802.11 networks. Two general mechanisms are proposed and evaluated: Reactive Duplicate Avoidance (RDA) and Proactive Duplicate Avoidance (PDA). The results demonstrate that both, RDA and PDA, reduce considerably the latency in industrial networks in comparison with other existing solutions. In a more recent work [11], authors present a Wi-Red prototype based on 802.11 commercial modules. The system overcomes the performance of existing mechanisms, such as Parallel Redundancy Protocol (PRP). The same authors have also studied the problems of mutual interference between channels in spatial diversity schemes [12].

Finally, there is a group of proposals based on various Cooperative MAC solutions [13]. The main idea of Cooperative MACs is the help of neighboring nodes in forwarding data packets to specific destination nodes when necessary. An interesting example is shown in [14], where a cooperative MAC

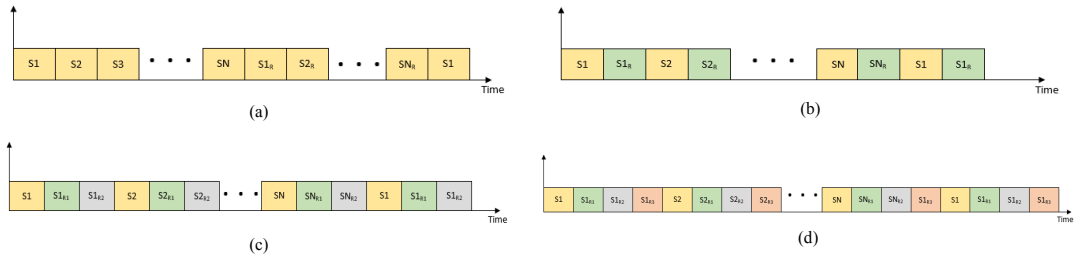


Fig 2. Proposed time and spatial diversity based retransmission schemes: (a) Time division retransmissions, (b) Retransmissions with two APs, (c) Retransmissions with three APs, (d) Retransmissions with four APs

protocol with rapid relay selection (RRS-CMAC) is presented. RRS-MAC selects an optimal relay whenever the data rate between the source and the destination is low or whenever the link performance shows a degraded behavior. The main benefit of this protocol is to improve the cooperation efficiency and multiple access performance in wireless ad hoc networks. In addition to reliability, cooperative MAC solutions have also been proposed for addressing other challenges, such as energy consumption in sensor networks. An example can be found in [15], where authors propose a distributed energy adaptive location-based CMAC protocol, namely DEL-CMAC, for Mobile Ad-hoc Networks (MANET) with optimized energy consumption.

In conclusion, although enhancements in reliability have been addressed by several authors, there are still challenges for applying wireless communication standards in industrial propagation channels. This is why, this paper analyzes the feasibility and performance of spatial diversity techniques under highly challenging channel conditions.

III. PROPOSED DIVERSITY SCHEMES

A. Time division retransmissions

The first mechanism that has been taken into account is time redundancy: retransmissions on a time division based scheme. As described in Section II, there are several options to handle retransmissions. In this work, intra-superframe retransmissions have been used, since they are considered more balanced than the other schemes in terms of maximum manageable latency. Therefore, the transmitter node sends the information required for each receiver within a control cycle. Then each communication is retransmitted redundantly (see Fig 2.a).

On the one hand, it is important to highlight the low complexity level of this scheme, without any extra cost nor synchronization penalties.

On the other hand, just one transmitter is used for both, transmissions and retransmissions, which means that the same link path will be applied to transmissions and retransmissions. In consequence, this scheme is vulnerable to long fading effects. Additionally, there is not any intelligence or feedback (no uplink is implemented), and so, retransmissions are redundant no matter the standard packet reception success. From the capacity point of view, this scheme divides the overall

TABLE I. SIMULATED CONFIGURATIONS

Retransmissions	# of Transmitters	Redundancy Level (R)	MCS
No	1	0	BPSK 1/2
Time based	1	1	QPSK 1/2
Spatial diversity	2	1	QPSK 1/2
Spatial diversity	3	2	QPSK 3/4
Spatial diversity	4	3	16QAM 1/2

capacity offered by the transmitter by two. So, higher MCS (Modulation and Coding Scheme) would be required to maintain the original throughput.

B. Spatial diversity based retransmissions

This second approach can be considered a complementary mechanism for the previous proposal, especially for highly challenging propagation channels. In this case, spatial diversity is applied on the transmitter side. Several transmitters will be introduced to increase path diversity. Ideally, N number of transmitters could be introduced. In this work up to four transmitters have been considered.

The main benefit of this technique lies in the uncorrelation of paths between each transmitter and the receiver, which will minimize simultaneous fading occurrences. Moreover, the impact of individual fading events on one link will be less critical. Furthermore, the higher the number of transmitters, the better performance is expected.

The maximum latency that a receiver will assume in a correct communication is very close to N number of packet air times. In comparison with the time division retransmissions solution, an interesting latency decrease is obtained.

However, the main drawback of this mechanism is that retransmissions are again redundant no matter the packet delivery success. So, the overall network capacity is proportionally reduced as a function of the number of transmitters. Therefore, a tradeoff has to be assumed between the offered capacity and the desired reliability.

IV. SIMULATION METHODOLOGY

In order to validate each of the proposed schemes, a dual simulator has been developed, consisting of a network simulator and a mathematical simulator. The first is used to

implement a complete communication network (OMNET ++), while the second is used to evaluate the system robustness under specific channel conditions (Matlab).

A transmitter-receiver prototype chain has been implemented in Matlab, which is fully compliant with the 802.11 a/g/n standard. Based on this prototype, PER vs. SNR curves are obtained for each MCS. This process takes into account all the effects of the channel and the characteristics of both transmission and reception. Therefore, the Matlab output for the 802.11 simulator could be considered a key performance indicator. The channel model is the so called “industrial channel” with Non-Line-Of-Sight (NLOS) condition and 29 ns rms delay spread defined in [16].

The network simulation tool (OMNeT++) is composed of both PHY and MAC layers. It is worth mentioning that in this prototype, the exponential backoff has been disabled in order to send transmission and retransmission frames inside controlled time slots. The PHY module facilitates the 802.11 MCS choice, as well as the length of each transmission slot and the airtime of each data packet. In addition, the MAC layer includes the implementation of the proposed access time schemes (see Fig. 2) and the access control to the transmission medium. Finally, the 802.11 performance curves obtained from Matlab as well as the channel impulse responses are loaded in OMNeT++ for full system simulation.

The simulations cover a range of mean received SNR values from 0 dB to 24 dB. For each simulation, a realization of the impulse channel response is assumed. Both effects, the channel impulse response and the mean SNR value, are combined to obtain the instantaneous SNR value. This instantaneous SNR value is used to evaluate packet reception success (one SNR value per packet). Finally, PER values are calculated independently in each receiver, and then, the mean PER value is calculated among all the receivers within the network. In fact, this is the performance evaluation metric that is going to be used to evaluate the reliability of each proposed and simulated scheme.

V. PERFORMANCE EVALUATION

The performance results of the schemes proposed in Section III are presented here.

A. Simulated configurations

Each simulation represents a sensor network spatial deployment within a manufacturing plant. The network is composed by two device classes: Access Points (APs) and Slaves. On the one hand, Slaves represent typical industrial sensors or actuators. On the other hand, the AP is the master node of both the architecture and the synchronization. The AP distributes information to all the devices connected to the network. The number of Slaves is fixed to 20 in each simulation, whereas the number of APs changes depending on the case.

For each mean SNR value, $2 \cdot 10^6$ superframes have been simulated. Furthermore, taking into account that the network is composed by 20 devices and that the PER value is obtained by averaging the results in each slave, for each configuration $4 \cdot 10^7$ superframes have been evaluated. This methodology leads to a

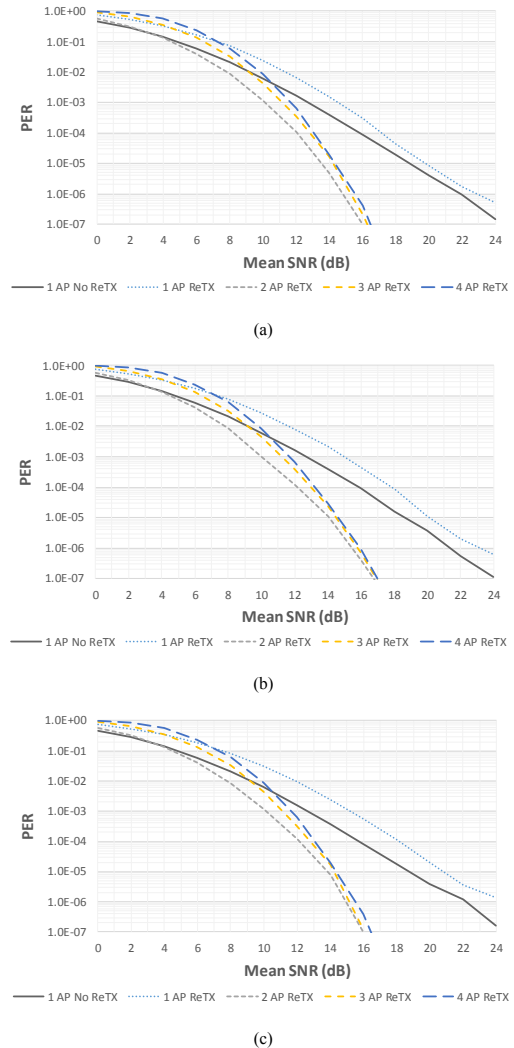


Fig 3. Performance PER vs. Mean SNR curves evaluation with redundant retransmissions for: (a) 30ms coherence time, (b) 50ms coherence time, (c) 100ms coherence time

minimum PER value close to 10^{-8} . Therefore, in order to show reliable results, each graphic will show PER values up to 10^{-7} .

Different diversity and retransmission schemes have been analyzed. First, a communication scheme without retransmissions is simulated. Undoubtedly, this is the simplest scenario and it will be the reference point for comparison purposes. After that, a time division retransmission scheme is implemented (see Fig 2.a). In this scheme, retransmissions are carried steadily and after having served every slave. Finally,

TABLE II. SNR THRESHOLDS FOR 10^{-5} PER

Retransmissions	# of Transmitters	$T_{\text{coh}} = 30\text{ms}$	$T_{\text{coh}} = 50\text{ms}$	$T_{\text{coh}} = 100\text{ms}$
No	1	18.8 dB	18.7 dB	18.8 dB
Time based	1	19.8 dB	20.1 dB	20.9 dB
Spatial diversity	2	13.5 dB	13.9 dB	13.8 dB
Spatial diversity	3	14.2 dB	14.5 dB	14.2 dB
Spatial diversity	4	14.3 dB	14.6 dB	14.3 dB

spatial diversity based retransmissions are simulated based on Fig 2.b, Fig 2.c and Fig 2.d, where two, three and four APs are needed. Retransmissions are redundant information for the slaves no matter the communication success, and they are carried out by the extra APs in order to obtain independent paths. This case assumes that the distance between APs is large enough to provide uncorrelated propagation AP-Slave paths.

Redundancy provokes an overall capacity decrease. For example, in the time division retransmission scheme and in the spatial diversity based scheme with two APs, the overall capacity is divided by two. Generalizing this approach, it can be said that:

$$\text{Useful capacity} = \frac{T_x \text{ capacity}}{R + 1} \quad (1)$$

where R is the redundancy level (see Table I) and Tx capacity is the capacity obtained by implementing the 802.11 standard. If the same throughput has to be offered to the network devices, transmitters have to transmit using higher MCS values, so, useful capacity decrease needs to be compensated. In this work, a constraint has been assumed before defining the offered services: the transmitters have to offer a minimum useful capacity of 6 Mbps. The effect of the constraint is shown in Table I in the MCS column. As shown, the higher the redundancy level, the higher is the required MCS value and the lower the modulation and coding robustness. Anyway, the reliability gain expected from spatial diversity based retransmissions should be high enough to compensate this issue.

Finally, the channel coherence time, a specific feature of industrial channels has been also considered. This parameter shapes the channel impulse response. In fact, the lower the coherence time, the faster the change of the channel impulse response. The coherence time is expected to have a significant impact on the time domain retransmission schemes, whereas, its effect should be almost negligible on spatial diversity based schemes. These assumptions have been evaluated with tests in three channel conditions, associated to channel coherence time values of 30, 50 and 100ms.

B. Results

All the results obtained from simulations are gathered in Fig 3. Three curves are presented, one for each channel coherence time. Each curve shows the reliability performance of each mechanism by plotting the obtained PER for a specific mean SNR value.

Regarding the effect of the channel coherence time, it has a remarkable effect over time division retransmission schemes

(light dotted blue line). Comparing it with the no retransmission scheme (dark solid grey line), the higher is the coherence time; the worse is the performance of the time division based retransmissions scheme. In each case, for 30ms, 50ms and 100ms of channel coherence time (Fig 3.a, Fig 3.b and Fig 3.c, respectively), time division based retransmissions are unable to offer better performance than the scheme with no retransmissions. This makes time based solution no longer feasible. This effect appears because of the constraint that states that all services have to guarantee at least 6 Mbps. On the other hand, spatial diversity solutions seem to be independent from the effect of the channel coherence time, since they offer in the three cases very similar results.

The difference between the performance tendency for time and spatial diversity technologies is also remarkable. The first group has a very flat PER decrease, which means that very high SNR values are required to guarantee reliable PER values. In other words, the performance of time division based schemes does not converge fastly. However, spatial diversity based schemes present faster reliability decrease while increasing the SNR. The overall tendency is more similar to waterfall performance curves, with fast convergence.

Analyzing in detail spatial diversity based mechanisms, a point, which should particularly be noted, is that using two AP (light dashed grey line) offers always the best performance for low SNR values. Nevertheless, three AP schemes (yellow dashed line) and four AP schemes (dark dashed blue line) curves converge slightly faster than two AP case. This effect is denoted in very low PER values where the difference among mechanisms is smaller than in higher error rates.

Another interesting point is the similar performance of spatial diversity based schemes. Despite the fact that increasing the number of transmitters involves a relevant change on network architecture, the spatial diversity based results are very similar. The increase in reliability derived from using higher number of independent paths is compensated with the increase needed in the MCS value in order to maintain the minimum throughput.

Another perspective of the reliability is shown in Table II. In this table, the SNR thresholds for a PER value of 10^{-5} are shown for each simulated case. Generally, a remarkable difference is found between time and spatial diversity schemes. Time based mechanisms require SNRs around 20 dB, with a maximum value of 20.9 dB. However, required SNR for spatial diversity schemes is always below 15 dB. All in all, SNR values around 14 dB are still a challenge in many harsh industrial environments.

As regards time requirements, each of the proposed and simulated solutions leads to a determined maximum latency

value. As packets are not retransmitted in other cycle times, latency can be predicted in this way:

$$\max \text{latency} = (R + 1) * \text{packet airtime} \quad (2)$$

where each packet airtime varies depending on the used MCS. Hence, the lowest maximum latency values are obtained by using the two AP schemes. As it is obvious, propagation time has not been included because it is almost negligible in comparison with packet airtime values.

On the whole, taking into account each of the presented discussion topics, the mechanism that includes two APs with spatial diversity based retransmissions is the most suitable option, since it offers the lowest error rate, a fast convergence and the lowest maximum latency with minimum complexity.

VI. UPPER RELIABILITY BOUND

Although the proposed schemes offer remarkable gains, they are a suboptimal solution, since reliability gain is partially sacrificed for maintaining throughput. Doubtlessly, this drawback is still compensable by avoiding the use of default retransmissions and replacing them with smart and/or efficient retransmission schemes.

Some reference works already available in the literature include smart retransmission schemes. The proposal referred as SHARP [5], proposes an ACK based retransmissions system to avoid the retransmission of each packet if that is not required. Moreover, in [10] several approaches are presented based on Duplicate Avoidance (DA) mechanisms, again to avoid redundancy in cases where is not required.

Furthermore, the success key for a smart retransmission scheme is to obtain independent physical channels on each path. In that way, the fading effect that transmissions and retransmissions suffer are uncorrelated. Consequently, theoretically, the relation between the PER value and the number of paths can be defined as:

$$\text{PER}_{N \text{ AP}} = (\text{PER}_{1 \text{ AP}})^N \quad (3)$$

where N is the number of APs in the network, and so, the number of independent paths.

The implementation of a DA mechanism that enables transmission and re-transmissions without any capacity constraint is analyzed in this section. Specifically, based on [10], we are assuming the use of PDA mechanisms that aim at preventing unnecessary transmissions.

Thus, no matter how many APs are used for transmitting, the most robust MCS value has been used in each simulation (MCS 0, BPSK 1/2). Regarding the simulated mechanisms and the channel coherence time, the same combinations as in Table I and Fig 3 have been used. All the results obtained from simulations are gathered in Fig 4.

On the one hand, time division based retransmission schemes are more vulnerable to the influence of the propagation channel coherence time. In fact, these curves do not converge except for high SNR values. Moreover, as it was expected, the gain obtained in reliability by applying time division based

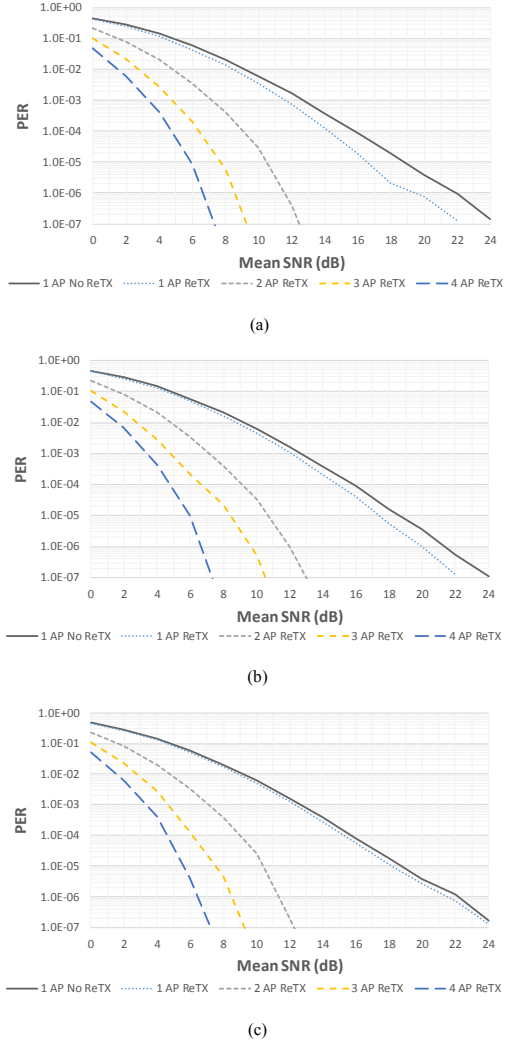


Fig 4. Performance PER vs. Mean SNR curves evaluation with smart retransmissions schemes for: (a) 30ms coherence time, (b) 50ms coherence time, (c) 100ms coherence time

retransmissions is higher in the 30ms coherence time case (see Fig 4.a), and it is almost negligible in the 100ms case (see Fig 4.c).

On the other hand, spatial diversity techniques show independence among the number of transmitters and the channel coherence time. In fact, results for spatial diversity cases are almost constant in relation to the coherence time. Furthermore, these curves have a clear converging tendency.

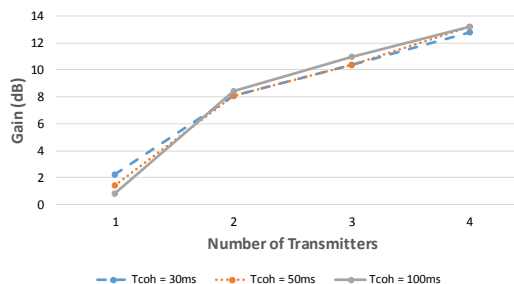


Fig 5. Spatial diversity gain with smart retransmission schemes

The main difference between curves presented in Fig 3 and the ones shown in Fig 4 lies in the relevance of the number of transmitters. Fig 4 shows that the higher the number of transmitters (dark dashed blue line, 4AP), the more reliable the communication, whereas using two AP (light dashed grey line) is the case that provides less gain.

In order to have an in-depth point of view of the gain obtained by applying smart or efficient retransmission systems, Fig 5 is added. In this figure, the x-axis of the graphic represents the number of transmitters working in the network and the y-axis represents the gain by using the current retransmission scheme in relation to not retransmitting at all. The gain is calculated at a SNR threshold equivalent to a 10^{-5} PER value.

The relevance of the channel coherence time is demonstrated again. In the case of a single transmitter, the highest gain is obtained for 30ms (dashed blue line), which is around 2.2 dB, whereas the lowest gain is obtained for 100ms (solid grey line), 0.8 dB. This effect demonstrates the channel state dependence for the time division retransmission schemes. However, in the cases involving spatial diversity, channel dependence disappears and almost the same gain is obtained for each number of transmitters, no matter the channel coherence time.

Another interesting aspect in Fig 5 is the change in the overall gain if additional transmitters are included. In this case, the biggest difference appears when the second AP is introduced. In that situation, up to 7.6 dB are obtained in the 100ms case. If more APs are added to the network, the gain continues increasing but not as fast as in the first case. Moving from two AP to three, around 2.3-2.6 dB are obtained, and changing from three to four, the gain is below 2.5 dB. This behavior means that the gain obtained by adding transmitters to the network and to the retransmission schemes is logarithmic. That is why, the curve grows fast at the beginning, but it slows down at the same time that the number of transmitters is increased. In the case this experiment could be done for any transmitter number, it could be demonstrated that the curve will saturate at a certain value. Generally, when a smart retransmission scheme is implemented, a tradeoff must be assumed between the required reliability, and the complexity and the costs derived from enlarging the network.

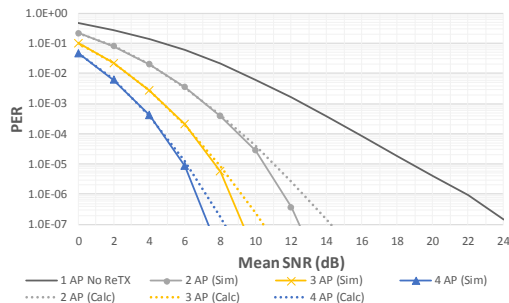


Fig 6. Simulated and calculated PER comparison for 30ms coherence time

Moreover, based on Eq. (3), the theoretical PER curves for two, three and four independent paths have been calculated taking as a reference the simulations that do not include retransmissions. Results for a channel coherence time of 30 ms are presented in Fig 6. Calculated PER curves are represented with the same color as its simulated pair, whereas they are characterized with dotted lines. Several comments can be done based on Fig 6. Firstly, it is remarkable the high similarity rate between calculated and simulated curves at least up to PER 10^{-5} . This means that the simulated conditions are similar to the ideal case where physical channels are uncorrelated. Therefore, the proposed situations are very close to the existing upper reliability bound, where no improvement can be achieved because the optimum configuration is already in place. It is also important to highlight the different behavior that curves have for PER values below 10^{-5} . This mismatch is derived from the tendency of the original curve, the scheme that does not include retransmissions (dark solid grey). This curve does not converge, even if high SNR values are assumed and that effect is indirectly included as well in the calculated curves.

VII. FUTURE WORK

This paper has analyzed comprehensively the use of spatial diversity techniques with the PHY level of the 802.11n standard, whereas there are still several open issues.

Based on this study, the first proposal will be to enhance diversity. A first approach could be to introduce more than four APs, test how the reliability increases and obtain a generic expression that estimates the gain associated to each hypothetical situation. Moreover, still with low number of APs, some intelligence could be applied to diversity algorithms. For example, the time for switching between APs could be directly related with the deep fading events appearing frequency of the channel, instead of using one AP just to retransmit.

A second area is the combination of these approaches with more sophisticated cooperative MAC solutions. In this case, new relay paths will be presented by using neighbors, other networks or even different technologies. While implementing this wider concept, different parameters can be taken into account, such as energy consumption.

Finally, frequency hopping could be also introduced as a complementary technique. Even if interferences and noise will not be fully eliminated, better performance is expected, due to the change of phase and amplitude of the reflected paths.

VIII. CONCLUSIONS

In this article, a comprehensive proposal of several techniques to increase communication reliability has been presented. The focus has been put on spatial diversity based schemes, which aim to fight against challenging channel time coherence conditions. Those techniques have been integrated in the 802.11n standard and the performance results have been presented. Results have been organized in two main groups: plain redundant retransmission schemes and smart retransmission schemes.

In the first approach, a relevant gain is easily obtained by retransmitting from different transmitters in order to create independent gains. However, transmitting redundant information affects directly the overall offered capacities. If the same throughput has to be offered to the network devices, transmitters have to transmit using higher MCS values. Consequently, the gain obtained by introducing more than two independent paths is almost cancelled with the MCS increase. This effect automatically presents the two AP spatial diversity based retransmissions case as the best alternative to guarantee low error rate, assuming the lowest complexity.

On the other hand, in the second approach, redundancy is avoided if not necessary by using smart retransmission schemes. In this case, the higher the number of transmitters, the lower the error rate. The increase has an almost logarithmic shape. Thus, the most beneficial situation is the introduction of the second transmitter in order to switch to spatial diversity based mechanisms.

In parallel, it has also been demonstrated that time channel coherence time does only affect time division retransmission schemes. The introduction of independent paths cancels the effect of the coherence time.

ACKNOWLEDGEMENTS

This work has been partially supported by the Spanish Government (project PHANTOM under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE)) and by the Basque Government under the PREDOC grant program (PRE_2018_1_0344), the project IOTERRAZ (under the grant KK-2019/00046, ELKARTEK 2019) and the Grant IT1234-19.

REFERENCES

- [1] R. Drath and A. Horch, "Industrie 4.0: Hit or Hype? [Industry Forum]," in *IEEE Industrial Electronics Magazine*, vol. 8, no. 2, pp. 56-58, June 2014.
- [2] P. Schulz et al., "Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture," in *IEEE Communications Magazine*, vol. 55, no. 2, pp. 70-78, February 2017.
- [3] F. Tramarin, S. Vitturi, M. Luvisotto and A. Zanella, "On the Use of IEEE 802.11n for Industrial Communications," in *IEEE Transactions on Industrial Informatics*, vol. 12, no. 5, pp. 1877-1886, Oct. 2016.
- [4] M. Luvisotto, Z. Pang and D. Dzung, "Ultra High Performance Wireless Control for Critical Applications: Challenges and Directions," in *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1448-1459, June 2017.
- [5] Ó. Seijo, Z. Fernández, I. Val and J. A. López-Fernández, "SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks," 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS), Imperia, 2018, pp. 1-10.
- [6] IEEE, «Orthogonal frequency division multiplexing (OFDM) PHY specification.» de 802.11 Standard - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, New York, United States of America, IEEE Computer Society, 2012, pp. 1583-1630.
- [7] M. Jonsson and K. Kunert, "Towards Reliable Wireless Industrial Communication With Real-Time Guarantees," in *IEEE Transactions on Industrial Informatics*, vol. 5, no. 4, pp. 429-442, Nov. 2009.
- [8] A. Willig, "How to exploit spatial diversity in wireless industrial networks," *Annu. Rev. Control*, vol. 32, no. 1, pp. 49-57, Apr. 2008.
- [9] S. Girs, E. Uhlemann and M. Björkman, "The effects of relay behavior and position in wireless industrial networks," 2012 9th IEEE International Workshop on Factory Communication Systems, Lemgo, 2012, pp. 183-190.
- [10] G. Cena, S. Scanzio and A. Valenzano, "Seamless Link-Level Redundancy to Improve Reliability of Industrial Wi-Fi Networks," in *IEEE Transactions on Industrial Informatics*, vol. 12, no. 2, pp. 608-620, April 2016.
- [11] G. Cena, S. Scanzio and A. Valenzano, "A Prototype Implementation of Wi-Fi Seamless Redundancy with Reactive Duplication Avoidance," 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), Turin, 2018, pp. 179-186.
- [12] G. Cena, S. Scanzio and A. Valenzano, "Improving Effectiveness of Seamless Redundancy in Real Industrial Wi-Fi Networks," in *IEEE Transactions on Industrial Informatics*, vol. 14, no. 5, pp. 2095-2107, May 2018.
- [13] D. O. Akande, M. F. M. Salleh, and F. K. Ojo, "MAC protocol for cooperative networks, design challenges, and implementations: a survey," in *Telecommunication Systems*, 1-17, 2018.
- [14] K. Liu, X. Chang, F. Liu, X. Wang, and A. V. Vasilakos, "A cooperative MAC protocol with rapid relay selection for wireless ad hoc networks" in *Computer Networks*, vol. 91, 262-282, 2015.
- [15] X. Wang and J. Li, "Improving the Network Lifetime of MANETs through Cooperative MAC Protocol Design," in *IEEE Transactions on Parallel and Distributed Systems*, vol. 26, no. 4, pp. 1010-1020, April 2015.
- [16] A. F. Molisch et al., "IEEE 802.15.4a channel model-final report," *IEEE P802*, vol. 15, no. 04, pp. 1-41, 2004.

3.2.4 Aldizkari-artikulua (A5)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengo da:

- E. Iradier, L. Fanari, I. Bilbao, J. Montalban, P. Angueira, O. Seijo, I. Val, "Analysis of NOMA-Based Retransmission Schemes for Factory Automation Applications," in *IEEE Access*, vol. 9, pp. 29541-29554, 2021, doi: 10.1109/ACCESS.2021.3059069.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 61/266 (Q1) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,745

Received February 2, 2021, accepted February 10, 2021, date of publication February 12, 2021, date of current version February 24, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3059069

Analysis of NOMA-Based Retransmission Schemes for Factory Automation Applications

ENEKO IRADIER¹, (Graduate Student Member, IEEE),
LORENZO FANARI¹, (Graduate Student Member, IEEE),
IÑIGO BILBAO¹, (Graduate Student Member, IEEE),
JON MONTALBAN¹, (Senior Member, IEEE), **PABLO ANGUEIRA**¹, (Senior Member, IEEE),
OSCAR SEIJO², (Member, IEEE), AND **IÑAKI VAL**², (Senior Member, IEEE)

¹Department of Communication Engineering, University of the Basque Country (UPV/EHU), 48013 Bilbao, Spain

²IKERLAN Technology Research Centre, Basque Research and Technology Alliance (BRTA), 20500 Mondragón, Spain

Corresponding author: Eneko Iradier (eneko.iradier@ehu.es)


This work was supported in part by the Basque Government under Grant IT1234-19, in part by the PREDOC under Grant PRE_2020_2_0105, and in part by the Spanish Government through project PHANTOM (MCIU/AEI/FEDER, UE) under Grant RTI2018-099162-B-I00.

ABSTRACT New use cases and applications in factory automation scenarios impose demanding requirements for traditional industrial communications. In particular, latency and reliability are considered as some of the most representative Key Performance Indicators (KPI) that limit the technological choices addressing wireless communications. Indeed, there is a considerable research effort ongoing in the area of wireless systems, not only from academia, but also from companies, towards novel solutions that fit Industry 4.0 KPIs. A major limitation for traditional wireless architectures is related to the harsh nature of the industrial propagation channel. Accordingly, this paper addresses these challenges by studying the reliability and latency performance of the joint use of different retransmission schemes in combination with Non-Orthogonal Multiple Access (NOMA) techniques. Two general retransmission schemes have been tested: time-based and spatial diversity-based retransmissions. An adaptive injection level NOMA solution has been combined with the retransmission schemes to improve the reliability of critical information. In all cases, a particular set of simulations has been carried out varying the main parameters, such as modulation, code rate and the injection level. Moreover, the impact of the number of transmitters in relation to the communication reliability has been analyzed. Results show that spatial diversity-based retransmissions overcome considerably the reliability obtained with time-domain retransmissions while maintaining assumable latency rates.

INDEX TERMS 802.11, factory automation, industry 4.0, LDM, NOMA, P-NOMA, retransmissions, spatial diversity, wireless communications.

I. INTRODUCTION

Wireless communications are considered one of the most challenging and promising research areas of the so-called Industry 4.0 [1], [2]. In fact, the high costs and the lack of scalability and mobility that traditional automated processes composed by wired control systems have to assume make this solution less efficient than wireless systems. Moreover, the deployment of wireless systems provides the opportunity to enhance traditional systems by introducing new capabilities.

The associate editor coordinating the review of this manuscript and approving it for publication was Bijju Issac .

However, the main challenge is the deployment scenario. Industrial environments entail strict requirements that are still hard to meet by wireless technologies, especially in the Factory Automation (FA) cases. For instance, very low latency values (0.25-10 ms) and ultra-high reliability (error rates below to 10^{-9}) are required [3], [4]. Determinism is another mandatory condition that is difficult to achieve with current wireless standards. In recent literature, in order to enable a massive deployment of industrial wireless networks, several technologies and standards have been proposed: IEEE 802.11 [5], [6], Bluetooth [7], 802.15.4 [8], LTE [9], and 5G [10], [11]. However, the latest versions of Wi-Fi and 5G stand out among all of them for a considerable improvement in critical

applications. On the one hand, the next generation Wi-Fi standard (i.e., IEEE 802.11be) will offer, among other things, full-duplex multi-channel communications, which makes it easier to meet the reliability and latency requirements established by the industry [12]. On the other hand, 5G also presents conditions to meet industrial requirements due to its PHY/MAC layer with a wide range of possible configuration parameters. Among them, 5G allows to use small OFDM symbols (i.e., below $10 \mu\text{s}$) with very robust modulation and code rates [13].

Since current standard wireless technologies do not cope with the demanding requirements of industrial applications and future standards such as 5G or IEEE 802.11be are still far from industrial deployment, some researchers have proposed proprietary solutions in order to get close to those barriers. For example, in [14], [15], Luvisotto *et al.* proposed the joint optimization of the PHY and MAC layers, improving the PHY reliability in several orders of magnitude and reducing the system latency by introducing a reliable MAC layer. In [5], [16], the authors follow the same joint PHY and MAC optimization approach in the solution referred to as SHARP (Synchronous and Hybrid Architecture for Real-time Performance). SHARP is based on the 802.11g standard and adds determinism to the PHY and MAC layers. In order to obtain competitive reliability and latency values, on the one hand, PHY frame aggregation techniques are implemented. On the other hand, a TDMA-based MAC structure with controlled time-division retransmissions is designed to guarantee a deterministic behavior.

A different strategy, based on improving the architecture of the access network is explored in [17], where several MAC level techniques in combination with the Wi-Fi PHY layer in challenging wireless channels are tested. Introducing multiple transmitters provided a reliability gain range of 8-12 dB. Specifically, the tests evaluated the use of two, three and four transmitters and they showed a non-linear behavior of the reliability increase while increasing the number of transmitters. Recently, in [18], the performance of spatial diversity with multiple redundant transmitters for mobile industrial communications is experimentally evaluated in a testbed with mobile robots. Authors implemented diversity using the Multipath TCP (MPTCP) protocol, which allows establishing different TCP connections between a transmitter and a receiver using multiple disjoint paths. The results indicate that redundant retransmissions improve reliability without compromising latency.

In [19], the use of Non-Orthogonal Multiple Access (NOMA) in combination with the IEEE 802.11n standard to meet the strict industrial requirements is considered. These results show that NOMA has the potential for enabling highly robust communications for industrial environments. However, the combination of NOMA and retransmission techniques has not been evaluated as a potential way to get closer to the performance requirements of current industry communications.

Therefore, in this paper, we propose and evaluate the joint use of NOMA and different diversity schemes to enhance the latency and reliability in industrial wireless networks. The diversity schemes are based on temporal and spatial diversity-based retransmissions using NOMA. Besides, some guidelines and recommendations are presented for real hardware implementation. In summary, the technical contributions of this paper include:

- 1) A comprehensive analysis of the PHY performance of a combined 802.11n and NOMA transceiver.
- 2) An analysis of the Injection Level (IL) capability to enhance the reliability.
- 3) A detailed analysis and performance evaluation of time-domain retransmissions.
- 4) Proposal and evaluation of combined multiple transmitter retransmissions with NOMA techniques.
- 5) Proposal and evaluation of a MAC layer that includes time, spatial and layer division.

The rest of the paper is organized as follows. The next section describes the related work, including the basis of NOMA techniques and state-of-the-art of retransmission and diversity schemes. Section III is focused on the presentation of the industrial use case and the simulation methodology. In Section IV, the PHY/MAC layers of the NOMA-based 802.11n transceiver are presented and evaluated. Then, in Section V, time-domain retransmissions are tested. Section VI is focused on the design and evaluation of MAC schemes that include multiple synchronized transmitters. Afterward, in Section VII a MAC layer that includes time, space and power multiplexing is designed and evaluated. Then, the latency and reliability results of the three different solutions are discussed and compared in Section VIII. Finally, Section IX contains the conclusions of the article.

II. RELATED WORK

This section contains, first, an overview of NOMA techniques and, then, a state-of-the-art of retransmission schemes including spatial diversity.

A. NOMA: GENERAL CONCEPTS AND INDUSTRIAL APPLICABILITY USING 802.11

NOMA represents a set of different medium access techniques where the receivers use the resource (either space, frequency, and time) in a non-orthogonal way. According to [20], NOMA techniques can be divided into two main families: code-domain NOMA (C-NOMA) [21], [22] and power-domain NOMA (P-NOMA) [23], [24]. In particular, although both NOMA families have been repeatedly proposed as alternatives to be included in 3GPP standards [25], P-NOMA techniques have shown a better complexity/performance tradeoff than C-NOMA [20]. During the rest of the paper, NOMA will refer to P-NOMA.

NOMA consists of different signals organized in several layers, where each layer takes some part of the transmitted total power. Each layer of the NOMA ensemble can be independently configured in order to address different reception

targets. Each NOMA configuration depends on the modulation and the coding choices assigned to each layer, and on the injection level (Δ , measured in dB), defined as the power splitting ratio among layers.

The main benefit of NOMA in comparison with classical TDM/FDM systems is the increase in spectral efficiency [26].

In [19], the first approach of a NOMA-based 802.11n system was proposed for FA environments. In this work, the communication architecture (PHY/MAC) of the 802.11n standard to include NOMA features was redesigned. Then, the proposed architecture was evaluated and the results showed a considerable better performance than the 802.11n standard PHY on several industrial use cases. In [27], a specific application of the NOMA-based solution was proposed for an industrial multimedia content broadcasting environment.

However, the reliability obtained in the previous works is still not enough for the most challenging industrial applications. Following the approach taken in previous works [14], advances in PHY reliability can be complemented with different MAC level techniques. Specifically, it is expected that MAC layer enhancements can improve the 10^{-4} Packet Error Rate (PER) provided by the physical layer down to 10^{-8} . That is why, in this paper, different MAC level techniques are proposed and implemented in combination with the NOMA-based 802.11n prototype.

B. RETRANSMISSIONS AND DIVERSITY SCHEMES

In communication systems, especially in industrial environments, the design of a robust PHY layer goes together with an efficient MAC layer. Among others, the main functionalities of the MAC layer are: the management of the transmission/reception instants based on the traffic requirements and on the wireless medium conditions, the configuration of the PHY layer, and the implementation of diversity mechanisms. One of the most widespread techniques is the use of retransmissions [28], with a variety of different configurations.

First, the authors in [17] evaluate time-domain retransmissions over 802.11n jointly with a TDMA scheme for different time-spacings between the first transmissions and the concurrent retransmissions. They determine that the effectiveness of these methods and the latency associated with them are closely related, since the more time that passes between transmission and retransmission, the greater the probability of success, but the greater the latency. In [29], the authors point out that wireless interferences can appear with different characteristics of intensity and duration. Therefore, they propose a MAC layer with temporal diversity that adapts the retransmissions to the characteristics of the interferences. The results show that their proposal can be applied for different types of information, meeting the requirements of real-time communications.

The retransmission of erroneous packets is also considered in cellular network technologies (i.e., LTE and 5G) and that is performed through Hybrid Automatic Repeat reQuest (HARQ) techniques. In particular, HARQs imply

that instead of retransmitting the entire packet, only a portion of the packet or extra redundant information is retransmitted to demodulate the original packet. In [30], the authors propose the use of a new early HARQ scheme based on LDPC sub-codes (SC E-HARQ). This technique decreases the overall latency since enables to start with the feedback calculation before the entire codeword is received. Results indicate that latency values below one millisecond can be obtained for Block Error Rate (BLER) values of less than 10^{-4} . Then, in [31], authors focus their study on delay-constrained scenarios and propose a fast HARQ protocol where in order to decrease the latency some feedback signals and successive messages are disabled. Different transmission rounds are tested and the latency results are reduced up to 60% in the case with five transmissions. Finally, in [32], HARQ techniques are combined with NOMA for the uplink of short packet communications. Simulations include one retransmission per user and coordinated and uncoordinated transmissions. Results show that NOMA-HARQ systems outperform orthogonal multiple access techniques for specific power and latency constraints.

Other authors have also investigated different retransmission schemes, such as [33], where a series of reliability tests using retransmissions are carried out in a laboratory environment. A combination of spatial and frequency diversity over four different RF channels is tested. The results indicate that under certain channel conditions, PER values close to 10^{-7} can be obtained. Later, in [34], different retransmission schemes based on the IEEE 802.15.4 standard are evaluated and compared. The authors conclude that PER values below 10^{-7} are possible with a maximum latency of 3 ms over a one-to-two transmission network with a 30 MHz frequency hop. Finally, in [35], the use of a backup wireless network is proposed to deal with errors. In particular, the authors propose two different models, one based on static redundancy and the other dynamic. The results show that both solutions significantly improve the reliability of the system.

Redundant and spatial diversity based transmissions have led to the development of new communication architectures. One approach is based on "Parallel Redundancy Protocol" (PRP) [36], which was originally developed to achieve seamless redundancy for Ethernet networks requiring high availability. Different works have proposed wireless PRP-like approaches such as [37], where PRP is used as diversity method on the wired Ethernet interfaces of two independent IEEE 802.11 WLAN channels that operate in parallel links. In [38] and [39], the same authors extended their study including the use of PRP for WLAN networks from different points of view such as reliability or latency. Specifically, reliability is measured for different noise levels, different jamming situations, and different packet lengths. In addition, they offer latency and jitter measurements in which they show that the use of PRP considerably improves its performance. Finally, in [40], the use of PRP for sensor networks in a star network configuration is proposed. The MAC level simulations show that when one of the two channels used for redundancy is

interfered with, the latency and jitter are improved by 121% and 376%. However, when both channels suffer interference, the improvement is drastically reduced.

Redundancy over Wi-Fi has been recently investigated under the name of Wi-Red (Wi-Fi Redundancy) [41]. Wi-Red aims at providing seamless link-level redundancy in IEEE 802.11 networks for industrial reliable wireless communications. The authors propose two working mechanisms depending on the complexity/reliability tradeoff: Reactive Duplicate Avoidance (RDA) and Proactive Duplicate Avoidance (PDA). From a latency perspective, the authors carried out several tests, where they conclude that both, RDA and PDA, reduce considerably the latency in industrial networks in comparison with other existing solutions. Then, in [42], the authors implemented a Wi-Red prototype using commercial 802.11 devices and they proved with a set of experiments that Wi-Red was able to enhance the latency and reliability in real industrial scenarios.

III. FA USE CASE AND EVALUATION PROCEDURE

This section contains the description of the use case implemented in this work and the evaluation procedure followed to tested the proposed solutions.

A. USE CASE

In this work, the use case emulates a small manufacturing cell with FA requirements [43]. Given that it is a reduced space (i.e., 10×10 m), it is assumed that the maximum number of nodes is 20. The network is made up of two types of equipment: Access Points (AP) and nodes. The former is in charge of distributing the information and of the synchronization tasks. On the contrary, the nodes are mainly receivers of the information or the commands sent by the APs. APs and nodes are organized in a centralized topology, where all the nodes receive data from the AP and send back their feedback in a timely organized manner. The diagram of the implemented architecture is shown in Fig. 1, where each node is connected to each AP in the network. Since industrial applications require deterministic communications, the wireless devices are preconfigured to transmit at specific time instants. As depicted in the figure, M indicates the number of nodes, N the number of APs, and γ the period of time between the communication of a node with two different APs. The information transmitted on the network is classified into two types: Critical Service (CS) and Best Effort (BE) service. CS is critical information that requires high reliability rates and low latency. Instead, BE is non-critical information, where the reliability and latency requirements are more flexible. Therefore, CS is configured with the lowest Modulation and Coding Scheme (MCS) (i.e., BPSK 1/2) and BE is configured with higher MCS that provide higher data rates (i.e., QPSK 1/2 - 16QAM 1/2). Regarding the size of the packets, as in [19], the size of the CS information packet has been set at 18 bytes, while for the BE the size is flexible.

Industrial scenarios are characterized by harsh wireless propagation conditions. To perform a realistic evaluation,

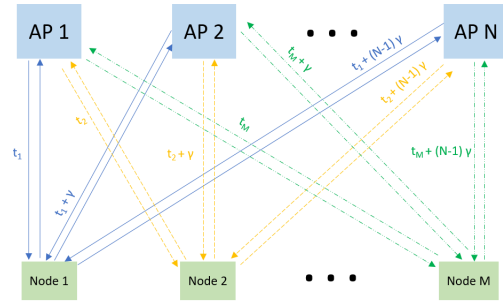


FIGURE 1. Network architecture.

two standard industrial wireless channels have been used, namely, CM7 and CM8 [44], which represents two industrial scenarios with different propagation properties. Although the CM7 and CM8 channels were initially generated based on IEEE 802.15.4a networks, the fact that there are no specific IEEE 802.11n models for industrial environments makes them a suitable candidate for our research purposes. For example, [45] describes several standard channel models for 802.11, but none of them reflects the characteristics of industrial environments. Concerning particular features of CM7 and CM8 channel models, the former represents line-of-sight (LOS) conditions, while CM8 is oriented to non-LOS (NLOS) conditions. As described in [44], channel measurements were carried out in larger enclosures (i.e., factory halls), filled with a large number of metallic reflectors, which implies a severe multipath effect. Moreover, the model was obtained following different measurements that cover a range from 2 to 8 m and frequency band from 2 to 10 GHz. As an example, Fig. 2 shows the channel gain time variability of three uncorrelated realizations of the CM7 channel.

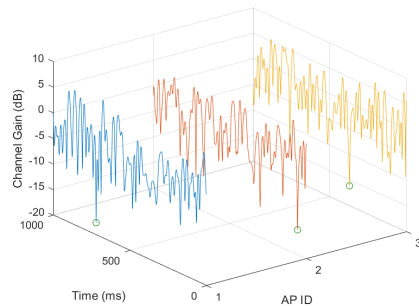


FIGURE 2. CM7 channels obtained from different APs.

The rest of the parameters related to the use case are shown in Table 1.

B. EVALUATION PROCEDURE

The evaluation procedure described in this subsection has been applied to the technical solutions proposed in the

TABLE 1. Use case parameters.

Parameter	Value
Application	FA
Center Frequency	2.4 GHz
Bandwidth	40 MHz
Channel model	CM7 - CM8
Type of Devices	AP and Nodes
Number of Nodes	Up to 20
Cell Size	10 x 10 m
Critical Service (Mbps)	12 Mbps
Non-critical Service (Mbps)	Up to 48 Mbps
Critical Service Payload	18 Byte

following sections. The simulations are based on a software tool designed on purpose for this work. It comprises a mathematical simulator (Matlab) and a network simulator (OMNeT++ [46]). The objective of the first one is the characterization of the reliability under a certain propagation channel while the second one emulates the communication network.

At the beginning of this work, different versions of the 802.11 standard were considered. In the first place, versions older than 802.11n were discarded due to the lack of LDPC codes. Afterwards, the 802.11ac standard was also discarded due to its higher overhead when compared with 802.11n. Finally, the 802.11ax standard presents configurations with similar or even better overhead than 802.11n since it incorporates several novelties, such as the trigger-frame based OFDMA medium access [47]. However, the 802.11ax transceiver presents a much higher complexity than 802.11n and its combination with NOMA may present several challenges. That is why it has been opted to use 802.11n and maintain a tradeoff between complexity and the performance parameters of industrial environments (i.e., reliability and latency) [6].

Concerning the implementation part, in a first step, a transmitter-receiver 802.11n standard chain has been implemented in Matlab [48]. Based on this implementation, several modifications have been carried out in the PHY level to introduce NOMA as a multiplexing option [19]. In addition, the transmitter-receiver chain also implements channel phenomena simulations, including fast-fading, free space loss, etc. To carry out the simulations, packets are sent assuming different channel realizations, and then, in reception, it is evaluated whether the packet has been correctly received or not. Each packet transmission set is performed for different Signal-to-Noise Ratio (SNR) values, with steps of 0.25 dB. The number of simulated packets and the SNR simulation steps have been adapted to the expected PER values. In particular, the simulated packet number is always at least one order of magnitude higher than the required value for obtaining the desired PER value assuming one single error.

In a second step, the network simulation tool is fed with the results obtained with Matlab. In particular, the PHY level performance measurements for different SNR values are introduced in OMNeT++ in order to use them in the

error calculation block. Then, the network simulation tool comprises the network level simulation of both PHY and MAC layers. On the one hand, the PHY module facilitates parameters closely related to the physical layer, such as the MCS choice, the length of each transmission slot and the airtime of each data packet. On the other hand, the MAC layer implements the diversity schemes and the medium access control mechanisms. Since OMNeT++ does not support NOMA communications, NOMA has been modelled in OMNeT++ through two independent data flows in the same transmission period. Then, in the reception stage, both data flows are individually and orderly managed (i.e., first data in the UL, then, the data in the LL if UL is successfully recovered).

To decide if a packet is erroneous, this methodology uses the receiver instantaneous SNR. As shown in [49], it is difficult to quantify the uncorrelation grade of two channels with different paths within the same environment, and it is not possible to completely uncorrelate those channels. Therefore, in this work, a case of partial uncorrelation is assumed, where the instantaneous SNR of each node has been modeled as a combination of two components: the mean SNR, which is a static value that depends on the reception characteristics, and the variable attenuation of the channel which varies with time:

$$SNR_{i,k} = \theta_i + \alpha_{i,j,k}, \quad (1)$$

where i identifies the node, j the AP, and k is the time when the transmission takes place. On the other hand, θ is the mean SNR and the variable attenuation of the channel is α . To carry out the simulations with this model, for each path, an independent evolution of the channel variability is assumed (α), where a new channel is generated by varying the generation seed. In Fig. 2, three examples of three different CM7 channels are shown. It should be noted that the three examples have similar behavior since the channel varies with similar rate. However, the minimum fading of each channel (i.e., green circle in the figure) occurs at different moments, which indicates that despite having a similar long-term trend, the instantaneous attenuation at each time point is uncorrelated.

IV. PHY/MAC DESIGN

This section shows, on the one hand, the reliability performance that could be obtained solely with the PHY layer, and, on the other hand, the general architecture of the MAC layer and the retransmission techniques presented afterwards.

A. PHY LAYER

The development of this section is based on [19], and therefore, the transmitter-receiver chain, as well as the NOMA signal generation and cancellation have not been modified. However, this subsection extends the previous work by focusing on the effect of the IL and the MCS of the Lower Layer (LL). The IL ranges from a case where the LL is injected a few decibels below the Upper Layer (UL) (i.e., 5 dB) to cases where LL is deeply buried (i.e., 20 dB). The LL signal

configuration choices are, first, a robust configuration (i.e., MCS1, QPSK 1/2) and, then, a case with doubled capacity and reduced robustness (i.e., MCS3, 16QAM 1/2). On the other hand, the MCS0 is always selected for the UL in order to guarantee high reliability cases. The channel model used in the simulations is the CM7.

Fig. 3, contains the UL performance curves for different injection values (from 5 to 20 dB range). The best result occurs for an IL of 20 dB and provides a SNR requirement of 2.1 dB for a PER value of 10^{-4} . Additionally, UL curves show that the SNR difference in the range [10,20] is insignificant (<1 dB). In consequence, following analyses of the UL behaviour will focus only on the IL range from 5 to 10 dB.

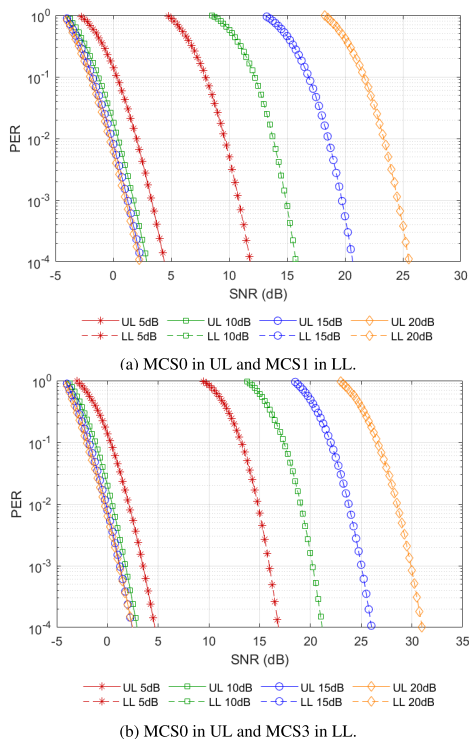


FIGURE 3. PHY layer performance for different injection level values and MCS configurations under CM7 propagation channel.

The impact of IL is a two-fold problem because the performance of the LL has to be taken into account as well. The difference among the cases for the LL is more evident. The gap between LL curves is the IL value. Also, for a given IL, the difference between MCS1 and MCS3 is close to 5 dB, which is approximately the performance difference between both MCS configurations. Looking at the LL SNR thresholds for a PER value of 10^{-4} , the results obtained with both 15 and 20 dB lead to SNR thresholds well above 20 dB and look unrealistic for industrial application. IL values of 5 and 10 dB

are the most suitable ones since they provide assumable SNR values for the LL.

The same simulations for the CM8 channel model have been carried out and the results are very similar (see Fig. 3). In general, when the CM8 channel model is used, the reliability performance shows a degradation between 0.1 dB and 0.3 dB. Given the similar performance trend in both channel model conditions (CM7 and CM8), the rest of the results presented in the following sections are based only on the CM7 channel model.

B. MAC LAYER

To meet the strict requirements associated with FA environments, PHY techniques have to be combined with efficient MAC level tools. In particular, an adequate MAC layer can potentially improve the reliability, guarantee bounded latency and increase the determinism of the overall communication system. In this section, the description of a MAC layer proposal and the different techniques described in the following sections are introduced.

Fig. 4 shows a time diagram of the superframe structure, which is based on TDMA in order to guarantee deterministic medium access to all the network devices. Three type of blocks can be identified: Downlink CS + BE transmission, Uplink Feedback (UF) and On-demand retransmissions. The first block is the initial transmission of both the critical and best-effort services. This transmission occurs in the downlink, from the AP to each of the nodes. Each downlink slot has a duration of $70 \mu\text{s}$ because is the minimum time required to transmit the 18 bytes of the CS (see Table 1) by using the lowest and most robust MCS (i.e., MCS0, BPSK 1/2). Furthermore, as the network is made up of 10 nodes the total length of the first block is $700 \mu\text{s}$. Then, the uplink feedback phase begins, in which each node informs individually the AP (using each node a dedicated time slot) whether or not the CS and BE services have been correctly received (i.e., ACK/NACK). This information is sent in single-layer mode using the most robust configuration (i.e., MCS0, BPSK 1/2). The duration of each slot is $54 \mu\text{s}$ since, in this case, only one OFDM symbol is required to transmit the ACK/NACK information. Once the feedback from the nodes is received, the AP retransmits only the packets reported as incorrect. That is, in case the node reports that both services, CS and BE, have been incorrectly received, the AP would retransmit CS and BE in two-layer mode. However, if the node reports that only the BE service is erroneous, the AP retransmits only the BE content in single-layer mode. This block has the same duration as the initial block. Finally, since the number of retransmissions is configurable, blocks two and three would be repeated until the configured number of retransmissions is reached.

Taking into account the superframe structure, the minimum and maximum latency values can be calculated. In the case of the minimum latency, this is obtained when the packet is delivered in the initial transmission block and, therefore, the $70 \mu\text{s}$ correspond to the duration of a transmission slot.

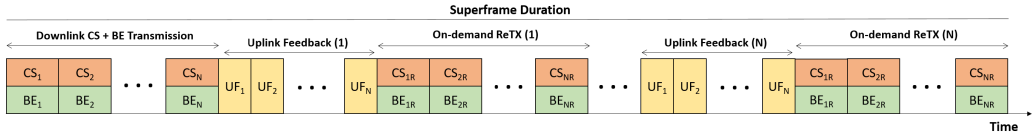


FIGURE 4. Superframe time representation.

On the contrary, the maximum latency value is obtained when the packet is received in the last on-demand retransmissions block. Therefore, the higher number of allowed retransmissions, the higher the maximum latency. That is why, up to three retransmission attempts are evaluated in order to keep assumable maximum latency values. Specifically, the maximum latency values are 1.24 ms, 2.48 ms and 3.72 ms for the one, two and three retransmissions, respectively.

Besides the flexibility in the number of retransmissions, the main difference with the superframe shown in [19] relies on the techniques used to carry out the retransmissions. In this case, in addition to the time-domain (see Section V), retransmissions with spatial diversity will also be implemented (see Section VI), where each one of the retransmissions is transmitted by a different AP. Finally, an additional retransmission mode is proposed. This alternative consists of using a higher injection level in the retransmissions to favor the correct reception of the CS packet (see Section VII). The following sections detail the design of each of the retransmission schemes and evaluate them from the point of view of reliability.

Although the MAC layer configuration presented in this section is specifically designed for the use case introduced in Section III-A, it would be possible to scale the MAC layer configuration to support more complex scenarios. For example, in a more heterogeneous case, there could be nodes that require only the CS, only the BE service, or both. In that case, each node should access the corresponding NOMA layer. If only the CS is needed, once the desired information has been decoded, the node would not access the LL layer. On the contrary, if only the BE service is required, the node should follow the entire decoding process associated with NOMA. However, note that the use of more nodes or with other configurations would not affect the overall reliability performance. Another variation could involve an industrial application built on top of the network architecture that requires a higher uplink traffic. In that case, the superframe could be modified to introduce more specific blocks for the uplink traffic. Furthermore, to introduce more uplink traffic, the medium could be managed through NOMA so that two nodes transmit the information simultaneously. However, this alternative would considerably increase the complexity of the receiver, since the IL between the layers would not be predetermined and would vary in each time slot and, therefore, at the receiver side, a block for estimating the IL would be necessary and/or transmitters should arrange their timing in advance [50].

V. TIME DOMAIN RETRANSMISSIONS

This section contains the design and evaluation of the combination between time-domain retransmissions with the NOMA-based 802.11n communications system.

A. DESIGN

This scheme follows the time diagram presented in Fig. 4, where the blocks of on-demand retransmissions are carried out by the same AP that made the initial attempt (i.e., single transmitter). Consequently, each node SNR for the retransmitted signal is highly correlated with the SNR received in the previous transmission. In particular, following Eq. (1), the only difference between the initial transmission and the retransmission is the temporal evolution of the channel (k), while the origin (j) and the destination (i) is the same.

These types of retransmissions offer better results under channels with high variability and lower time coherence. However, although they are not offering a meaningful gain in all cases in terms of reliability, it should be noted that they entail a very small increase in complexity and implementation cost.

B. EVALUATION

The reliability results obtained with time-domain retransmissions are presented in Fig. 5, which is based on PER and Packet Loss Rate (PLR) measurements. In this case, PER represents the performance when no retransmissions are used, while PLR is for cases with retransmissions. Firstly, the best reliability performance values for the UL are obtained in the 10 dB case, which presents a difference close to 2 dB in comparison with the worst case (i.e., IL 5 dB). When the number of retransmissions is increased, the gap is reduced. In this case, gains close to 4 dB, 6 dB and 7 dB are obtained for one, two and three retransmissions, respectively. Although the reliability performance is improved, the best case SNRs are still around 20 dB, which is considered too high for the critical services. LL shows a different behavior. Although different ILs have been used, the results obtained are very similar, since the retransmissions are done in single-layer mode.

In general, time-domain retransmissions improve reliability but not significantly since the coherence time of the channel is higher than the time between retransmissions. Furthermore, it is worth noting the gain provided by the case of one retransmission, since introducing the first retransmission improves reliability more than when introducing the second or third retransmission. However, it would be necessary to

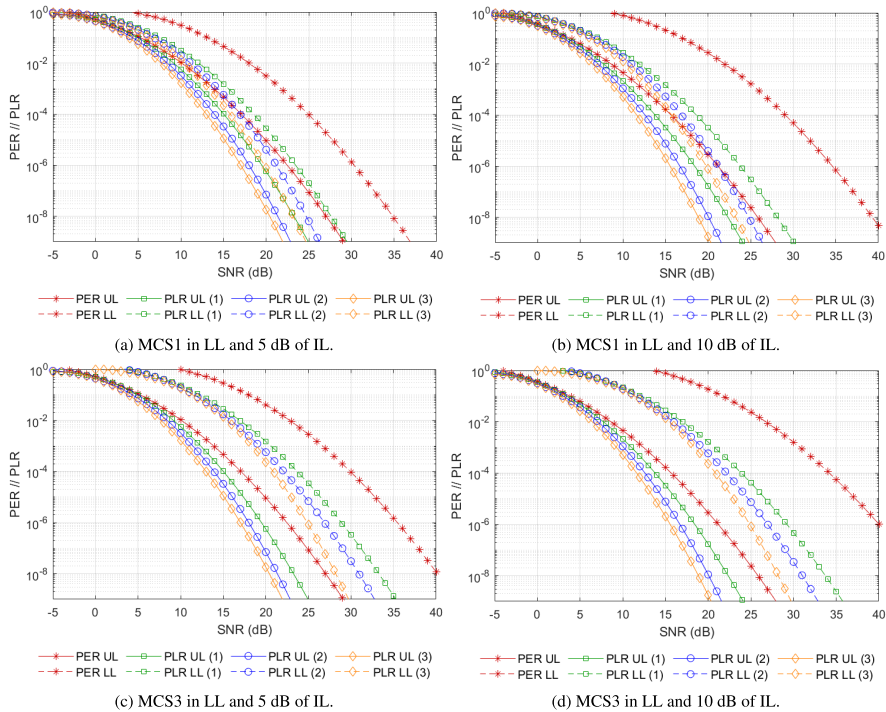


FIGURE 5. Reliability results obtained using a single transmitter with time-domain retransmissions under CM7 channel model and MCS0 in UL for different configurations.

evaluate depending on the target application which case best meets the reliability vs latency/complexity relationship.

VI. RETRANSMISSIONS FROM MULTIPLE TRANSMITTERS

This section shows the design and evaluation of combining retransmissions from multiple transmitters with NOMA.

A. DESIGN

The second technique belongs to the family of spatial diversity and consists of using multiple transmitters. Specifically, taking into account the structure of the superframe (see Fig. 4), each block of on-demand retransmissions will be delivered by a different AP. So if the number of retransmissions configured is N , the number of APs that make up the network has to be $N + 1$. In addition, in the UF period, each node will send its feedback information to the AP that sent it the data in the previous block. It is assumed that all the APs are connected and synchronized so that they all receive the information that the UF contains. Additionally, nodes are supposed to share a common time reference that grants interference free access to the medium as described in [51], [52].

The retransmissions are conveyed from a different AP, and thus, the initial transmission and the retransmission do

not follow the same propagation path. Specifically, according to Eq. (1), since the mean SNR (θ) is affected by the receiver and the implementation environment, it will remain constant for the different retransmissions. On the other hand, when varying the retransmission path using another AP, the characteristics of the variable attenuation will be quite uncorrelated (i.e., j).

Time/space retransmissions from multiple transmitters will improve the reliability offered by time-domain retransmissions. However, introducing this scheme in a network includes higher implementation and synchronization costs. Therefore, depending on the gain obtained in reliability and the type of target application, they could be decisive.

B. EVALUATION

The results are gathered in Fig. 6. First, it is observed that the UL results are considerably better than those obtained using time-domain retransmissions only. In particular, the best results obtained using three retransmissions are around 10 dB. The gain associated to one, two and three retransmission is close to 11, 15 and 18 dB, respectively and for any IL value. The case that implements single retransmission is already better than any of the cases presented in the previous section (see Section V).

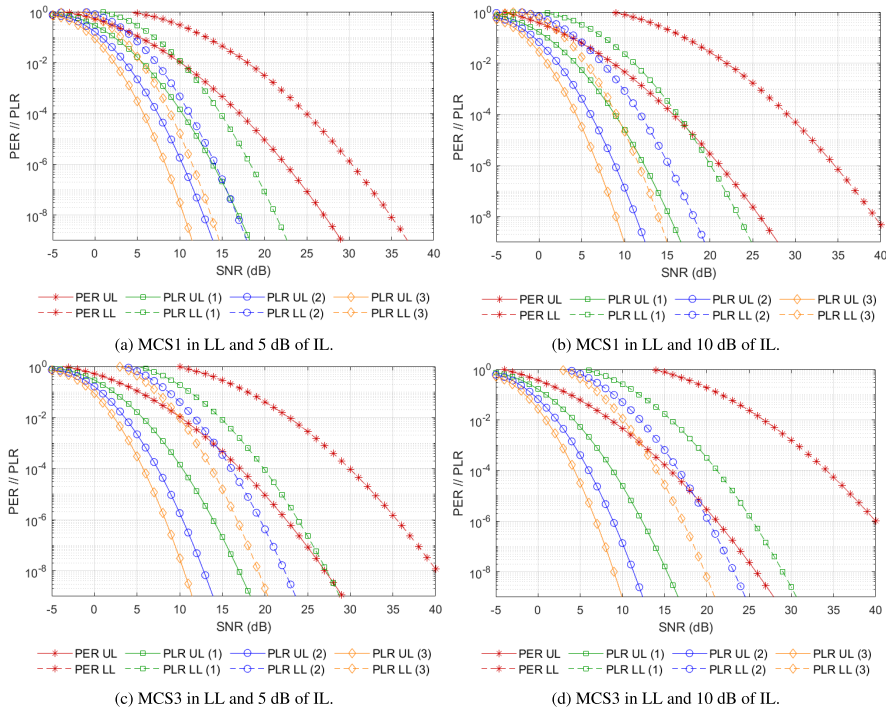


FIGURE 6. Reliability results obtained using retransmissions with multiple transmitters under CM7 channel model and MCS0 in UL for different configurations.

On the other hand, the results obtained for LL present a trend similar to that obtained in the previous section (see Section V). The case with the lowest reliability (i.e., MCS1 and 5 dB of IL) has gains of 14, 19 and 22 dB for one, two and three retransmissions, respectively. The case with the highest gain is that of the MCS3 with an IL of 10 dB, where 18, 24 and 28 dB are achieved for one, two and three retransmissions, respectively.

In general, the reliability obtained using multiple transmitters is greatly improved and the PLR rates obtained are applicable in mission-critical environments. However, an increase in complexity associated with the synchronization and deployment of APs has to be assumed. It is important to note that introducing a second AP is critical, since it provides a considerable increase in reliability. On the contrary, the differential gain provided by a third and fourth AP decreases significantly. Therefore, its implementation will depend on the use case and the reliability that needs to be addressed.

VII. RETRANSMISSIONS WITH VARIABLE IL

This section shows the design and evaluation of the combination of the retransmission techniques shown in the previous sections with adaptive injection levels.

A. DESIGN

This section presents a complementary technique to the previous time/space retransmissions. In this case, an adaptive injection level is proposed to increase the reliability of the UL. The adaptive IL provides a tool to make the UL more robust. If one of the nodes reports in the UF period that both services have been erroneously received, the AP retransmits the packets encoded with a larger IL, so that the LL impact is lower and the SNR required to decode the CS is lower also. However, in case the node has correctly received the CS and only needs the retransmissions of the BE service, the retransmission is carried out in single-layer mode. On the other hand, this technique does not present any additional complexity for the receiver nodes, since as in the UF period each node has requested the corresponding retransmissions if required, each node knows which IL is going to use the AP to encode the information. It should be noted that from now on the acronyms IL1 and IL2 represent the injection level used in the initial transmission and the one used for the retransmissions, respectively.

The adaptive injection level is a complementary technique to those schemes already evaluated in Section V and VI. Although the gain that can be obtained with this technique

is limited, the complexity involved is very low, so the reliability/complexity ratio offers an interesting alternative.

B. EVALUATION

Fig. 7 shows the results obtained using the adaptive IL method for all retransmission cases (i.e., time and space) using a different number of retransmissions (i.e., one, two and three). The gain represents the variation of the SNR required to achieve a PLR value of 10^{-9} when introducing the adaptive IL. Given that the gain obtained in all cases is similar and that it does not show a straightforward behavior, all cases have been grouped according to layer and MCS. In Fig. 7 the black whiskers represent the maximum and minimum values of each case, the blue lines represent the 25th and 75th percentiles and the red line the median value. Concerning the IL, for this case, IL1 has been set to 5 dB and IL2 to 10 dB.

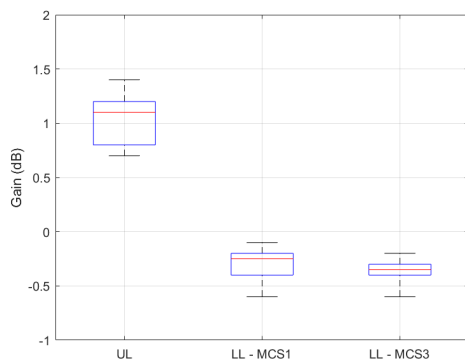


FIGURE 7. Improvement obtained with adaptive IL.

Fig. 7, proves that the performance of the UL layer is improved, assuming small losses in the LL layer. Specifically, the UL shows a median gain of 1.1 dB and taking into account that time retransmissions only provide around 4 dB of improvement with a single retransmission, it is a considerable gain. On the contrary, from the point of view of retransmissions using multiple transmitters, the gain is small compared to the values shown in Section VI-B. On the other hand, the LL reliability degrades. However, taking into account that LL is a BE service, and that degradation is lower than 1 dB, it is considered an acceptable performance loss.

VIII. COMPARISON OF PROPOSED RETRANSMISSION SCHEMES

This section compares all the solutions proposed in this paper in terms of the superframe and network size, reliability, and latency.

A. SUPERFRAME AND NETWORK SIZE

The number of nodes in the network or the duration of the superframe are also parameters to identify different industrial environments. FA, for instance, is more restrictive than

Process Automation (PA) in terms of time related parameters such as delay, jitter or update time [43]. Therefore, this section presents the estimation of superframe lengths and the number of nodes in the network using the superframe structure shown in Fig. 4.

First, Table 2 shows the necessary superframe duration for networks in which the number of nodes is pre-established. It should be noted that all cases with a single retransmission have a superframe duration below 10 ms. However, as the number of retransmissions increases, the length of the superframe increases considerably and exceeds FA limits.

TABLE 2. Superframe size for different number of nodes.

Number of Nodes	1 ReTX (ms)	2 ReTX (ms)	3 ReTX (ms)
2	0.39	0.64	0.88
5	0.97	1.59	2.21
15	2.91	4.77	6.63
20	3.88	6.36	8.84
30	5.82	9.54	13.26
40	7.76	12.72	17.68
50	9.70	15.90	22.10

Table 3 displays results from a different approach. We assume that the maximum duration of the superframe is fixed by the use case and limited by the application cycle period. In this case, the table shows the maximum number of nodes that can be included in the superframe. For example, the first case, where the superframe cannot exceed one millisecond, is an FA case where a very small cycle time is required. In that case, the superframe supports up to five, three, and two nodes using one, two, and three retransmissions, respectively. On the other hand, if the limit value of FA environments (i.e., 10 ms) is taken into account, the number of possible nodes is multiplied by ten. Finally, the last two cases are oriented to PA environments and the number of admissible nodes is an order of magnitude higher than in the case of 10 ms.

TABLE 3. Maximum number of nodes for different superframe sizes.

Superframe Length	1 ReTX	2 ReTX	3 ReTX
1 ms	5	3	2
5 ms	25	15	11
10 ms	51	31	22
50 ms	257	157	112
100 ms	515	314	226

B. RELIABILITY

In Fig. 8, the gain is calculated as the SNR difference in dB between the PER and the PLR required to have an error rate of 10^{-9} . The analysis is divided into three parts: UL, LL with MCS1 and LL with MCS3, which are represented in Fig. 8(a), Fig. 8(b) and Fig. 8(c), respectively.

In Fig. 8(a), the first conclusion is that retransmissions with multiple transmitters have a greater impact on the UL case. Regarding the adaptive injection level, it is observed that the reliability improves when using it but in a moderate

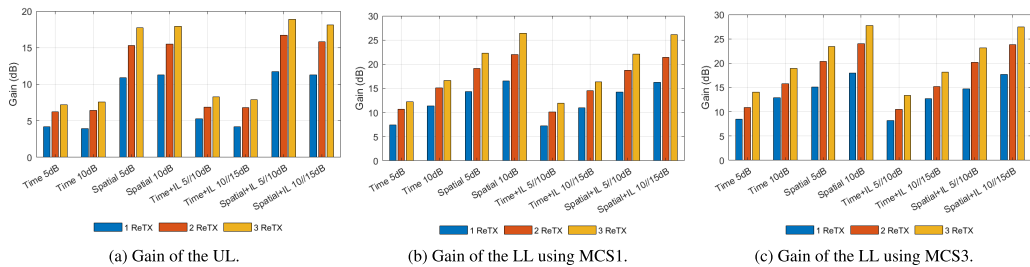


FIGURE 8. Comparison of the gain obtained by the different MAC techniques and for different configurations.

TABLE 4. Mean E2E latency analysis.

SNR	1 ReTX (μ s)				2 ReTX (μ s)				3 ReTX (μ s)			
	Time	Sp.	Time + IL	Sp. + IL	Time	Sp.	Time + IL	Sp. + IL	Time	Sp.	Time + IL	Sp. + IL
UL												
5 dB	118	207	157	216	172	241	200	234	235	248	245	237
10 dB	76	83	80	83	83	83	84	83	88	83	86	83
15 dB	70	70	70	70	71	70	70	70	71	70	71	70
LL using MCS1												
5 dB	960	950	962	977	1048	1281	1045	1218	1145	1424	1139	1311
10 dB	451	466	453	468	476	492	475	488	498	494	496	489
15 dB	132	133	132	133	134	133	134	133	135	133	135	133
LL using MCS3												
5 dB	1226	1224	1226	1226	1406	1800	1407	1751	1605	2293	1605	2213
10 dB	970	983	970	985	1057	1242	1057	1237	1155	1348	1155	1339
15 dB	461	478	462	478	485	500	486	500	507	501	508	501

way. Finally, increasing the number of retransmissions is more effective over retransmissions with spatial diversity, with overall gain values close to 20 dB in some cases.

On the other hand, in Fig. 8(b) and Fig. 8(c), the LL shows higher gains than the UL, due to the configuration of retransmissions in single-layer mode. The performance behavior depending on the configuration is quite similar, although in general, the LL configured with MCS3 shows a slightly higher gain than MCS1. Furthermore, in this case, although the difference in performance between time-domain retransmissions and with multiple transmitters is still evident, it has diminished considerably. On the other hand, it can be said that the use of the adaptive injection level does not affect the LL, since the losses are negligible. Finally, it is worth noting that there are several cases in both MCS1 and MCS3 that exceed 25 dB of gain.

C. E2E LATENCY

Latency is another critical parameter in FA environments, which in general is related to reliability since many of the techniques to improve reliability involve an increase in latency. Therefore, in this work latency and reliability are analyzed to give a global vision of performance. In this case, End-to-End (E2E) latency is used to represent the time that elapses since the transmission of a packet begins until it is finally received, including retransmissions if necessary. The most representative E2E latency values have been gathered

in Table 4. It shows the mean E2E latency values for different SNR values and each of the retransmission techniques. Specifically, the values shown for retransmissions in the time domain and with multiple transmitters have been obtained using an IL of 5 dB and those that use the adaptive injection level vary between 5 dB and 10 dB. Those cases have been chosen because they present the most balanced reliability results between UL and LL in the previous subsection. To calculate the mean latencies, three specific SNR values have been selected (i.e., 5, 10 and 15 dB). On average, the UL presents low latency values in which 250 μ s are not exceeded in any case. In fact, the latency values with 15 dB SNR are practically the same as the minimum value, which indicates a high reliability rate. In turn, as expected, the latency values for LL are higher than for UL. However, despite the low SNR values used, in no case do they exceed 2 ms and taking into account that it is a BE service, it is an acceptable rate. Furthermore, it should be noted that for the 10 dB and 15 dB SNR cases using MCS1 and the 15 dB case using MCS3, the maximum mean latency values are around 500 μ s.

Finally, if the latency values are analyzed as a function of the retransmission technique, it can be seen that the higher the reliability rate, the higher the average latency that must be assumed. That is why, the highest values appear in the case of multiple transmitters combined with adaptive IL since it is the case in which retransmissions are more efficient. The main reason for this is the success rate of the retransmission

TABLE 5. Analysis of the jitter results obtained for the UL.

SNR	1 ReTX (μs)				2 ReTX (μs)				3 ReTX (μs)			
	Time	Sp.	Time + IL	Sp. + IL	Time	Sp.	Time + IL	Sp. + IL	Time	Sp.	Time + IL	Sp. + IL
5 dB	114.37	114.06	114.43	114.26	194.57	168.27	194.16	168.41	226.62	203.50	226.21	203.54
10 dB	16.24	17.84	16.19	17.88	24.59	21.58	24.41	21.51	30.81	23.49	30.89	23.54
15 dB	0.81	0.82	0.77	0.85	0.98	0.88	0.96	0.89	1.12	0.87	1.06	0.89

schemes since error packets are not taken into account for the latency calculation. However, taking into account the gains in reliability that have been obtained in the previous section, the increase in latency is acceptable. Similarly, the more retransmissions that are used, the greater the latency that is obtained, since the size of the superframe is also lengthened.

To complement the E2E latency measurements, Table 5 shows the jitter values obtained for the UL with the same configurations as in Table 4. First of all, it should be noted that with an SNR of 5 dB the jitter values are quite high and even in some cases very close to the average latency. However, the jitter is greatly reduced when the SNR is increased. In particular, with 10 dB of SNR the jitter does not exceed 30 μs and with 15 dB the values are around one μs , which indicates that hardly any retransmissions are needed. Furthermore, in general, retransmissions based on multiple transmitters have better jitter values, since as they are more efficient, they require fewer retransmissions to guarantee the correct reception of the packets.

In summary, depending on the requirements of the final application, a compromise between latency and reliability has to be made.

IX. CONCLUSION

This paper presents and evaluates a set of techniques to increase communication reliability over the 802.11n standard. These techniques include the integration of NOMA within the 802.11n PHY layer, the use of a TDMA-based MAC scheme, and the use of different retransmission techniques in different diversity domains. To our best knowledge, this paper is the first to consider different retransmission schemes for a NOMA-based 802.11n communication system. In particular, time-domain and multiple transmitter based retransmissions have been combined with adaptive injection level and evaluated from the reliability and latency point of view.

The main conclusion is that each one of the evaluated retransmission techniques has its advantages and disadvantages. In particular, time-domain retransmissions are the simplest to implement, but also the ones that offer lower reliability due to channel dependence. However, it has been shown that by increasing the number of retransmissions, up to 7 dB of gain can be obtained for the CS. In contrast, retransmission schemes that include multiple transmitters have demonstrated much higher reliability rates. The main disadvantages of these techniques are the synchronization that is required and the deployment costs. The specific NOMA technique aimed at adapting the injection level to favor the reception of the

UL in retransmissions has shown moderate gain values, but it can be useful in cases where the highest reliability rate is needed. Moreover, the latency analysis indicates that the higher the reliability offered by the retransmission schemes, the higher the latency that the system has to assume. However, taking into account the type of services proposed and the requirements of industrial environments, the latency values obtained are below the limits. Therefore, depending on the final application, in order to decide the optimal solution, a tradeoff has to be evaluated and assumed between reliability and latency.

This paper is oriented to the combination of NOMA techniques with TDMA-based medium access, therefore, the next step is to integrate NOMA in OFDMA-based communication schemes such as 802.11ax/be standards. To do this, on the one hand, the necessary modifications in the current 802.11ax/be transceiver architecture will be studied, as well as the potential gains that could be obtained. In addition, the complexity implications of the introduction of NOMA should be measured and low-complexity alternatives should be proposed to improve the complexity/performance tradeoff.

REFERENCES

- [1] R. Drath and A. Horch, "Industrie 4.0: Hit or hype? [industry forum]," *IEEE Ind. Electron. Mag.*, vol. 8, no. 2, pp. 56–58, Jun. 2014.
- [2] A. Varghese and D. Tandur, "Wireless requirements and challenges in industry 4.0," in *Proc. Int. Conf. Contemp. Comput. Informat. (IC I)*, Nov. 2014, pp. 634–638.
- [3] P. Schulz, M. Matthe, H. Klessig, M. Simsek, G. Fettweis, J. Ansari, S. A. Ashraf, B. Almeroth, J. Voigt, I. Riedel, A. Puschmann, A. Mitschele-Thiel, M. Müller, T. Elste, and M. Windisch, "Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 70–78, Feb. 2017.
- [4] K. Montgomery, R. Candell, Y. Liu, and M. Hany, *Wireless User Requirements for the Factory Workcell* (Advanced Manufacturing Series (NIST AMS)), vol. 8. Gaithersburg, MD, USA: NIST, 2019.
- [5] O. Seijo, I. Val, and J. A. Lopez-Fernandez, "w-SHARP: Implementation of a high-performance wireless time-sensitive network for low latency and ultra-low cycle time industrial applications," *IEEE Trans. Ind. Informat.*, early access, Jul. 7, 2020, doi: 10.1109/THI.2020.3007323.
- [6] F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella, "On the use of IEEE 802.11n for industrial communications," *IEEE Trans. Ind. Informat.*, vol. 12, no. 5, pp. 1877–1886, Oct. 2016.
- [7] R. Rondón, M. Gidlund, and K. Landnäs, "Evaluating Bluetooth low energy suitability for time-critical industrial IoT applications," *Int. J. Wireless Inf. Netw.*, vol. 24, no. 3, pp. 278–290, Sep. 2017.
- [8] M. Anwar, Y. Xia, and Y. Zhan, "TDMA-based IEEE 802.15.4 for low-latency deterministic control applications," *IEEE Trans. Ind. Informat.*, vol. 12, no. 1, pp. 338–347, Feb. 2016.
- [9] I. Aktas, M. H. Jafari, J. Ansari, T. Dudda, S. A. Ashraf, and J. C. S. Arenas, "LTE evolution—Latency reduction and reliability enhancements for wireless industrial automation," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–7.

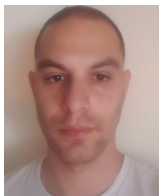
- [10] X. Jiang, M. Luvisotto, Z. Pang, and C. Fischione, "Latency performance of 5G new radio for critical industrial control systems," in *Proc. 24th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2019, pp. 1135–1142.
- [11] G. Hampel, C. Li, and J. Li, "5G ultra-reliable low-latency communications in factory automation leveraging licensed and unlicensed bands," *IEEE Commun. Mag.*, vol. 57, no. 5, pp. 117–123, May 2019.
- [12] D. Lopez-Perez, A. Garcia-Rodriguez, L. Galati-Giordano, M. Kasslin, and K. Doppler, "IEEE 802.11be extremely high throughput: The next generation of Wi-Fi technology beyond 802.11ax," *IEEE Commun. Mag.*, vol. 57, no. 9, pp. 113–119, Sep. 2019.
- [13] A. Slalmi, R. Saadane, A. Chehri, and H. Kharraz, "How will 5G transform industrial IoT: Latency and reliability analysis," in *Human Centred Intelligent Systems*. Singapore: Springer, 2020, pp. 335–345.
- [14] M. Luvisotto, Z. Pang, and D. Dzung, "Ultra high performance wireless control for critical applications: Challenges and directions," *IEEE Trans. Ind. Informat.*, vol. 13, no. 3, pp. 1448–1459, Jun. 2017.
- [15] M. Luvisotto, Z. Pang, and D. Dzung, "High-performance wireless networks for industrial control applications: New targets and feasibility," *Proc. IEEE*, vol. 107, no. 6, pp. 1074–1093, Jun. 2019.
- [16] O. Seijo, Z. Fernandez, I. Val, and J. A. Lopez-Fernandez, "SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks," in *Proc. 14th IEEE Int. Workshop Factory Commun. Syst. (WFCS)*, Jun. 2018, pp. 1–10.
- [17] E. Iradier, J. Montalban, L. Fanari, and P. Angueira, "On the use of spatial diversity under highly challenging channels for ultra reliable communications," in *Proc. 24th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2019, pp. 200–207.
- [18] M. C. Lucas-Estan, B. Coll-Perales, and J. Gosalvez, "Redundancy and diversity in wireless networks to support mobile industrial applications in industry 4.0," *IEEE Trans. Ind. Informat.*, vol. 17, no. 1, pp. 311–320, Jan. 2021.
- [19] J. Montalban, E. Iradier, P. Angueira, O. Seijo, and I. Val, "NOMA-based 802.11n for industrial automation," *IEEE Access*, vol. 8, pp. 168546–168557, 2020.
- [20] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, "Nonorthogonal multiple access for 5G and beyond," *Proc. IEEE*, vol. 105, no. 12, pp. 2347–2381, Dec. 2017.
- [21] R. Hoshyari, F. P. Wathan, and R. Tafazolli, "Novel low-density signature for synchronous CDMA systems over AWGN channel," *IEEE Trans. Signal Process.*, vol. 56, no. 4, pp. 1616–1626, Apr. 2008.
- [22] F. Brannstrom, T. M. Aulin, and L. K. Rasmussen, "Iterative detectors for trellis-code multiple-access," *IEEE Trans. Commun.*, vol. 50, no. 9, pp. 1478–1485, Sep. 2002.
- [23] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, I. Chih-Lin, and H. V. Poor, "Application of non-orthogonal multiple access in LTE and 5G networks," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 185–191, Feb. 2017.
- [24] E. Iradier, J. Montalban, L. Fanari, P. Angueira, L. Zhang, Y. Wu, and W. Li, "Using NOMA for enabling broadcast/unicast convergence in 5G networks," *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 503–514, Jun. 2020.
- [25] N. M. Balasubramanya, A. Gupta, and M. Sellathurai, "Combining code-domain and power-domain NOMA for supporting higher number of users," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.
- [26] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H. M. Kim, J.-Y. Lee, P. Angueira, and J. Montalban, "Layered-division-multiplexing: Theory and practice," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 216–232, Mar. 2016.
- [27] E. Iradier, J. Montalban, L. Fanari, P. Angueira, O. Seijo, and I. Val, "NOMA-based 802.11n for broadcasting multimedia content in factory automation environments," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jun. 2019, pp. 1–6.
- [28] M. Jonsson and K. Kunert, "Towards reliable wireless industrial communication with real-time guarantees," *IEEE Trans. Ind. Informat.*, vol. 5, no. 4, pp. 429–442, Nov. 2009.
- [29] P. G. Peon, E. Uhlemann, W. Steiner, and M. Bjorkman, "Applying time diversity for improved reliability in a real-time heterogeneous MAC protocol," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–7.
- [30] B. Goektepe, S. Faehse, L. Thiele, T. Schierl, and C. Hellge, "Subcode-based early HARQ for 5G," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2018, pp. 1–6.
- [31] B. Makki, T. Svensson, G. Caire, and M. Zorzi, "Fast HARQ over finite blocklength codes: A technique for low-latency reliable communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 1, pp. 194–209, Jan. 2019.
- [32] F. Ghanami, G. A. Hodtani, B. Vucetic, and M. Shirvanimoghaddam, "Performance analysis and optimization of NOMA with HARQ for short packet communications in massive IoT," *IEEE Internet Things J.*, early access, Oct. 2, 2020, doi: 10.1109/JIOT.2020.3028434.
- [33] H. Beikirch, M. Voss, and A. Fink, "Redundancy approach to increase the availability and reliability of radio communication in industrial automation," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom.*, Sep. 2009, pp. 1–4.
- [34] B. Kilberg, C. B. Schindler, A. Sundararajan, A. Yang, and K. S. J. Pister, "Experimental evaluation of low-latency diversity modes in IEEE 802.15.4 networks," in *Proc. IEEE 23rd Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, vol. 1, Sep. 2018, pp. 211–218.
- [35] P. G. Peon, W. Steiner, and E. Uhlemann, "Network fault tolerance by means of diverse physical layers," in *Proc. 25th IEEE Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, vol. 1, Sep. 2020, pp. 1697–1704.
- [36] H. Kirmann, M. Hansson, and P. Muri, "IEC 62439 PRP: Bumpless recovery for highly available, hard real-time industrial networks," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2007, pp. 1396–1399.
- [37] M. Rentschler and P. Laukemann, "Towards a reliable parallel redundant WLAN black channel," in *Proc. 9th IEEE Int. Workshop Factory Commun. Syst.*, May 2012, pp. 255–264.
- [38] M. Rentschler, O. A. Mady, M. T. Kassis, H. H. Halawa, T. K. Refaat, R. M. Daoud, H. H. Amer, and H. M. ElSayed, "Simulation of parallel redundant WLAN with OPNET," in *Proc. IEEE 18th Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2013, pp. 1–8.
- [39] M. Rentschler and P. Laukemann, "Performance analysis of parallel redundant WLAN," in *Proc. IEEE 17th Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2012, pp. 1–8.
- [40] M. Hendawy, M. ElMansoury, K. N. Tawfik, M. M. ElShenawy, A. H. Nagui, A. T. ElSayed, H. H. Halawa, R. M. Daoud, H. H. Amer, M. Rentschler, and H. M. ElSayed, "Application of parallel redundancy in a Wi-Fi-based WNCs using OPNET," in *Proc. IEEE 27th Can. Conf. Electr. Comput. Eng. (CCECE)*, May 2014, pp. 1–6.
- [41] G. Cena, S. Scanzio, and A. Valenzano, "Seamless link-level redundancy to improve reliability of industrial Wi-Fi networks," *IEEE Trans. Ind. Informat.*, vol. 12, no. 2, pp. 608–620, Apr. 2016.
- [42] G. Cena, S. Scanzio, and A. Valenzano, "A prototype implementation of Wi-Fi seamless redundancy with reactive duplication avoidance," in *Proc. IEEE 23rd Int. Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2018, pp. 179–186.
- [43] J. F. Coll, J. Chilo, and B. Slimane, "Radio-frequency electromagnetic characterization in factory infrastructures," *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 3, pp. 708–711, Jun. 2012.
- [44] A. F. Molisch, K. Balakrishnan, C.-C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, "IEEE 802.15.4a channel model-final report," *IEEE P802*, vol. 15, no. 4, p. 0662, Nov. 2004.
- [45] V. Erceg, L. Schumacher, and P. Kyriaki, *TGN Channel Models*, document IEEE 802.11-03/940r1, Garden Grove, CA, USA, 2004.
- [46] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Proc. 1st Int. ICST Conf. Simulation Tools Techn. Commun. Netw. Syst.*, 2008, p. 60.
- [47] B. Bellalta, "IEEE 802.11ax: High-efficiency WLANs," *IEEE Wireless Commun.*, vol. 23, no. 1, pp. 38–46, Feb. 2016.
- [48] *Orthogonal Frequency Division Multiplexing (OFDM) PHY Specification, de Standard—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Nueva York, Estados Unidos, Standard 802.11, IEEE Computer Society, 2012, pp. 1583–1630.
- [49] V. N. Swamy, P. Rigge, G. Ranade, B. Nikolic, and A. Sahai, "Wireless channel dynamics and robustness for ultra-reliable low-latency communications," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 4, pp. 705–720, Apr. 2019.
- [50] S. Abeywickrama, L. Liu, Y. Chi, and C. Yuen, "Over-the-air implementation of uplink NOMA," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.
- [51] O. Seijo, J. A. Lopez-Fernandez, H.-P. Bernhard, and I. Val, "Enhanced timestamping method for subnanosecond time synchronization in IEEE 802.11 over WLAN standard conditions," *IEEE Trans. Ind. Informat.*, vol. 16, no. 9, pp. 5792–5805, Sep. 2020.

- [52] A. Mahmood, R. Exel, H. Trsek, and T. Sauter, "Clock synchronization over IEEE 802.11—A survey of methodologies and protocols," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 907–922, Apr. 2017.



ENEKO IRADIER (Graduate Student Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of the Basque Country (UPV/EHU), in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree with the TSR Research Group. Since 2015, he is part of the TSR Research Group, UPV/EHU. He was with the Communications Systems Group, IK4-Ikerlan, as a Researcher, from 2017 to 2018. During his

doctoral studies, he did an internship with the Communications Research Centre Canada, Ottawa. His current research interests include design and development of new technologies for the physical layer of communication systems and wireless solutions for Industry 4.0. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications.



LORENZO FANARI (Graduate Student Member, IEEE) received the B.Sc. degree in electrical and electronic engineering and the M.Sc. degree in telecommunication engineering from the University of Cagliari, Italy, in 2015 and 2018, respectively. He is currently pursuing the Ph.D. degree with the University of Basque Country, Spain. His research interests include coding theory and wireless communications.



IÑIGO BILBAO (Graduate Student Member, IEEE) received the B.S. degree in physics and the M.S. in space science and technology from the University of the Basque Country (UPV/EHU), in 2019 and 2020, respectively, where he is currently pursuing the Ph.D. degree with the TSR Research Group. Since 2020, he is part of the TSR Research Group, UPV/EHU. His current research interests include design and development of new technologies for the physical layer of wireless solutions for Industry 4.0.



JON MONTALBÁN (Senior Member, IEEE) received the M.S. and Ph.D. degrees in telecommunications engineering from the University of the Basque Country, Spain, in 2009 and 2014, respectively. He is part of the TSR (Radiocommunications and Signal Processing) Research Group with the University of the Basque Country, where he is an currently an Assistant Professor involved in several research projects. He has hold visiting research appointments with the Communication

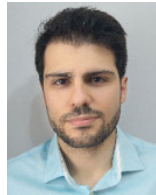
Research Centre (CRC), Canada, and Dublin City University (DCU), Ireland. His current research interests include wireless communications and signal processing for reliable industrial communications. He was a co-recipient of several best paper awards, including the Scott Helt Memorial Award to recognize the best paper published in the IEEE TRANSACTIONS ON BROADCASTING, in 2019. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications. He is currently serves as an Associate Editor for IEEE ACCESS.



PABLO ANGUEIRA (Senior Member, IEEE) received the M.S. and Ph.D. degrees in telecommunication engineering from the University of the Basque Country, Spain, in 1997 and 2002, respectively.

In 1998, he joined the Department of Communications Engineering, University of the Basque Country, where he is currently a Full Professor. He is part of the staff of the Signal Processing and Radiocommunication Laboratory, where he has been involved in research on digital broadcasting (DVB-T, DRM, T-DAB, DVB-T2, DVB-NGH, and ATSC 3.0) for more than 20 years. He is a coauthor of an extensive list of articles in international peer-reviewed journals, and a large number of conference presentations in digital broadcasting. He has also coauthored several contributions to the ITU-R working groups WP6 and WP3. His main research interest includes design and development of new technologies for the physical layer of communication systems in industrial wireless environments.

Dr. Angueira is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, a member of the IEEE BMSB International Steering Committee, and a Distinguished Lecturer of the IEEE BTS. He serves on the Administrative Committee for the IEEE BTS.



OSCAR SEIJO (Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of Oviedo, Spain, in 2015 and 2017, respectively. He is currently pursuing the Ph.D. degree with the Communications Systems Group, IKERLAN Technological Research Centre, Mondragón, Spain, in collaboration with the Signal Theory and Communications (TSC) Group, University of Oviedo. His research interests include wireless

high-performance PHY and MAC design for industrial applications, time synchronization over wireless systems, and digital signal processing.



IÑAKI VAL (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from the Department of Electronics Engineering, University of Mondragón, Spain, in 1998 and 2001, respectively, and the Ph.D. degree from the Department of Signals, Systems, and Radiocommunication, Polytechnic University of Madrid, Spain, in 2011. Since 2001, he has been with the Communications Systems Group, IKERLAN, Mondragón, Spain. He was with the Fraunhofer Institute for Integrated Circuits IIS, Erlangen, Germany, as an Invited Researcher, from 2005 to 2006. He is currently the Team Leader of Communication Systems Group. His research interests include design and implementation of digital wireless communications systems, industrial real-time requirements, communications for distributed control systems, vehicular communications, time synchronization, wireless channel characterization, and digital signal processing. He is currently focused on industrial communication applications.

...

3.2.5 Aldizkari-artikulua (A6)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- E. Iradier, A. Abuin, L. Fanari, J. Montalban and P. Angueira, "Throughput, Capacity and Latency Analysis of P-NOMA RRM Schemes in 5G URLLC," *Multimedia Tools and Applications* aldizkarian argitaratzeko onartua.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: Springer eta JCR-n indexatutako aldizkaria
- Saila: Konputazio zientziak, Software Ingeniaritza
- Sailkapena: 34/108 (Q2) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 2,313

Throughput, Capacity and Latency Analysis of P-NOMA RRM Schemes in 5G URLLC

Eneko Iradier¹, Aritz Abuin², Lorenzo Fanari³, Jon Montalban⁴, Pablo Angueira⁵

Abstract – 5G is expected to cover a wide range of potential use cases due to its flexible and configurable physical layer waveform. One of the use cases proposed is the application of 5G on Ultra-Reliable Low Latency Communication (URLLC), which are characterized by very challenging reliability/availability and latency requirements. In addition, multimedia applications are being consolidated as a relevant aspect of current industrial environments. In order to meet those strict requirements, Radio Resource Management (RRM) becomes a critical phase of any wireless communication system. This work proposes the use of power domain Non-Orthogonal Multiple Access (P-NOMA) techniques in 5G RRM for factory automation environments. The research presented in this paper includes the design and evaluation of different RRM algorithms based on P-NOMA and on traditional Orthogonal Multiple Access (OMA) techniques, such as Time/Frequency Division Multiplexing Access (T/FDMA). Those algorithms are comprehensively explained and oriented to optimize the resource allocation based on different metrics (i.e., capacity, number of users, or cycle time). Moreover, extensive results are presented, where the performance of NOMA and OMA techniques is compared in terms of different metrics under the influence of several parameters, such as payload, bandwidth, or the number of users. Results indicate that although both NOMA and OMA provide positive aspects, eventually NOMA-based RRM algorithms are the solutions that enhance considerably the spectral efficiency.

Keywords – 5G, Factory Automation, NOMA, P-NOMA, Resource Allocation, Resource Block, RRM, TDMA, URLLC, Wireless Communications.

Declarations:

Funding - This work was supported in part by the Basque Government (Project IOTERRAZ) under Grant KK-2019/00046 ELKARTEK 2019, Grant IT1234-19 and the PREDOC Grant Program PRE_2020_2_0105, and in part by the Spanish Government (Project PHANTOM) under Grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE).

Conflicts of interest/Competing interests - Not applicable

Availability of data and material - Not applicable

Code availability - Not applicable

¹ Department of Communications Engineering, University of the Basque Country, Bilbao, Spain. Email: eneko.iradier@ehu.eus. ORCID ID: 0000-0002-0424-3857

² Department of Communications Engineering, University of the Basque Country, Bilbao, Spain. Email: abuin003@ikasle.ehu.eus. ORCID ID: 0000-0003-4868-4029

³ Department of Communications Engineering, University of the Basque Country, Bilbao, Spain. Email: lorenzo.fanari@ehu.eus. ORCID ID: 0000-0001-8023-1973

⁴ Department of Electronic Technology, University of the Basque Country, Eibar, Spain. Email: jon.montalban@ehu.eus. ORCID ID: 0000-0003-0309-3401

⁵ Department of Communications Engineering, University of the Basque Country, Bilbao, Spain. Email: pablo.angueira@ehu.eus. ORCID ID: 0000-0002-5188-8412

1. Introduction

5G is expected to radically change wireless communications, not only from a qualitative point of view but also by widening the range of potential applications and use cases. The first step has been the standardization of 5G New Radio (NR) in Release 15 (Rel-15) [2]. 5G NR introduces several novelties in comparison with its predecessor (i.e., Long Term Evolution, LTE) at different levels. For example, it presents a configurable physical layer (PHY) that makes 5G a real candidate for applications with completely different requirements. In this release, there is also a considerable increase of the physical layer reliability due to the use of Low-Density Parity-Check (LDPC) codes for data content and Polar codes for control packets. The International Telecommunication Union Radiocommunication sector (ITU-R) has highlighted three main use cases (See Fig. 1) within the 5G framework [31]. The first, enhanced Mobile Broadband (eMBB) is oriented to data-driven use cases that require high throughput within a large coverage area. This use case is related to classical infotainment applications and extended to Augmented Reality (AR) and Virtual Reality (VR) applications. It is expected to overcome the Gbps barrier by offering up to 20 Gbps of peak data rate for the downlink and up to 10 Gbps for the uplink. The second use case is Ultra Reliable Low Latency Communications (URLLC), which targets mission-critical applications, such as remote surgery or autonomous vehicles [5]. These use cases imply strict requirements on latency and reliability [29]. In fact, a maximum end-to-end latency in the user plane of one millisecond has been established. Finally, the third use case is massive Machine Type Communications (mMTC), which focuses on Internet of Things (IoT) applications. In this case, the simultaneous connection of a very large number of devices has to be supported in small areas. The target device density is around 10^6 devices per square kilometer.

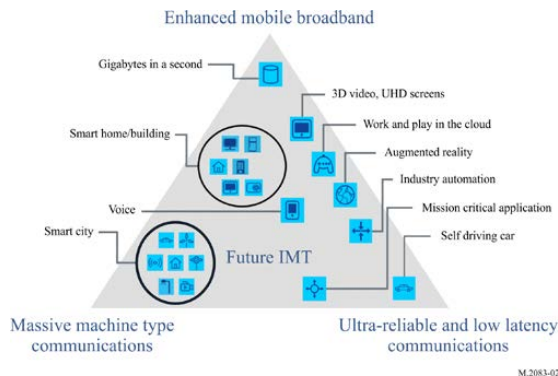


Fig. 1 5G NR applications and use case families [1]

Meanwhile, the second phase of 5G is being standardized in parallel by 3GPP in the Release 16 (Rel-16) and it is expected to be completed during 2020. Although Rel-15 was oriented to eMBB services, Rel-16 goes beyond and targets URLLC and mMTC services by introducing new features, such as Time Sensitive Communication (TSC) or Enhanced Location Services (ELS). Finally, the standardization process of Rel-17 has also taken off. In this case, it is in an initial phase and its first outcomes are expected for 2021. Rel-17 and further releases are oriented to support solutions to more global features, such as the convergence of wireless and wired systems, multicast and broadcast architectures, or multi-access edge computing [18].

URLLC is a wide use case closely related to the industry, where several applications can be included with considerably different requirements. In particular, in the last decade, there has been a considerable increase in the inclusion of multimedia applications within the industry. On the one hand, the use of AR is being promoted within different industrial applications, such as shipyards [9] [15]. Moreover, in [14], AR is used to deliver assembly instructions to workers. Finally, the authors in [17] propose and validate an extended reality (XR)-based framework that executes five typical iterative phases of industrial environments: requirements analysis, solution selection, data preparation, system implementation, and system evaluation. On the other hand, another classic aspect of the industry that is reinforced with the improvement of multimedia applications is video surveillance. Some representative examples are [21] and [36], where the use of video applications is proposed to automatically identify products in the steel industry and for

acquisition and self-learning autonomous surveillance services, respectively. Furthermore, in [7], a video-monitoring system with a distributed architecture is proposed. Finally, the authors in [16], through a more specific proposal, propose and design a multi-dimensional architecture based on video monitoring on MPEG-DASH (Dynamic Adaptive Streaming over HTTP).

In order to support the combination of multimedia applications with industrial characteristics, the network should support the simultaneous delivery of services with different requirements, such as unicast and broadcast services, loss tolerant and loss intolerant services, or downlink and uplink connections. Doubtlessly, the increase in the number of potential applications within a common cell makes the provision of high spectral efficiency a critical metric. As in LTE, Radio Resource Management (RRM) is based on orthogonal multiple access (OMA) techniques that share the available resource blocks (RB) among the users. However, although, if compared with LTE, the spectral efficiency has been improved considerably in 5G, there is still room for improvement in the RRM module.

This work proposes the introduction of non-orthogonal multiple access (NOMA) techniques in current RRM modules. NOMA techniques have demonstrated better spectral efficiency results than OMA [28]. In the literature, there are several proposals to use power domain NOMA (P-NOMA) to guarantee convergence of different services, while increasing the spectral efficiency [22] [47]. Indeed, both approaches have been focused on the study and the benefits of a P-NOMA-based PHY without taking into account the RRM level. However, this work is oriented to provide and evaluate different RRM algorithms.

The objective of this paper is to propose and evaluate the use of NOMA in RRM techniques for 5G URLLC in industrial environments. Two main multiplexing access techniques are considered in this paper: Time Division Multiplexing Access (TDMA) as a reference of OMA, and P-NOMA in the representation of NOMA techniques. Both alternatives are deeply analyzed from different perspectives (throughput, capacity, and latency) and optimized to meet different requirements (maximum capacity/throughput and minimum cycle time). Then, the parameters that affect the performance are identified and some guidelines are provided in order to decide the best performing multiplexing technique according to different parameter ranges.

In summary, the technical contributions of this paper include:

- Propose and evaluate TDMA for RRM in 5G URLLC and design several broadcast/unicast convergence algorithms.
- Propose and evaluate P-NOMA for RRM in 5G URLLC and design several broadcast/unicast convergence algorithms.
- Provide a detailed analysis of both alternatives in terms of throughput (ADR), capacity (served users), and latency (cycle time).
- Determine the best performing multiplexing technique according to a specific set of parameter ranges (payload size, maximum cycle time, bandwidth, and number of users).

The rest of the paper is organized as follows. Section 2 presents the basic principles of NOMA. An overview of the RRM in 5G for URLLC is also provided in that section. The industrial use case and the designed algorithms are introduced in section 3 and section 4, respectively. In section 5, the results obtained from evaluating the proposed algorithms in the industrial use case are presented and a summary is provided, where the best performing multiplexing technique is selected according to some specific parameter range. Finally, the conclusions and future works are highlighted in section 6.

2. Basic Principles

2.1. Basic principles of NOMA

NOMA represents a wide family of medium access techniques where all users share the same frequency and time resources. In fact, NOMA can be classified into code-domain NOMA [20] and power-domain NOMA [45]. This paper is focused on low complexity P-NOMA systems since they are considered less complex solutions [30]. During the rest of the paper, NOMA will refer to power domain NOMA.

NOMA refers to the signal ensemble composed of several superposed layers, where each layer takes a portion of the total power delivered by the transmitter. Generally, modulation and coding of each layer are

independently configured in order to offer different robustness and capacities. The injection level (Δ) describes the power splitting among layers in dB. A two-layer NOMA signal can be expressed as:

$$x_{NOMA}(k) = x_{s1}(k) + g \cdot x_{s2}(k), \quad (1)$$

where $x_{s1}(k)$ and $x_{s2}(k)$ are the two data streams combined into $x_{NOMA}(k)$, k is the subchannel index and g is the injection level expressed in linear units.

NOMA was firstly introduced by Cover and Bergmans in [8][11]. It was based on a technique called Successive Interference Cancellation (SIC), in which the receiver demodulates, decodes, and cancels successive information layers from the received signal ensemble. Layered Division Multiplexing (LDM) is a particular low-complexity case of NOMA [46], which presents an architecture that facilitates its implementation in real hardware elements. In addition, LDM also provided a considerable increase in spectral efficiency in comparison with OMA techniques. In fact, due to both reasons, complexity, and capacity, LDM was accepted as part of the latest digital television standard (ATSC 3.0) [37].

Power domain NOMA techniques have also been proposed to be used in broadband technologies. First, in [24] LDM was proposed in combination with LTE-Advanced (LTE-A) for multicast vehicular communications. Then, in [33], a more in-depth analysis of the use case was presented. In addition, the use of NOMA for enabling multicast subgrouping techniques in an evolved multimedia broadcast multicast service (eMBMS)-like 5G scenario was proposed in [33]. The latest works, such as [27], [22], and [47], are oriented to integrate NOMA in the PHY of 5G NR providing different capacity, reliability, and latency analysis where NOMA demonstrates that outperforms classical OMA techniques.

As an example of the advantages of NOMA, in Fig. 2, a representation of the spectral efficiency offered by several NOMA and T/FDMA configurations is shown for different Signal to Noise Ratio (SNR) requirements. It is important to highlight the effect of the service asymmetry: the higher the difference between the service requirements (i.e., the difference between the required SNR for each service), the higher the gain of NOMA. Specifically, the greatest gains are depicted for the services that combine SNRs of 0 dB and 20 dB. What is more, for a hypothetical value of 0.6 bps/Hz for service one, more than 2 bps/Hz of gain is achieved for service two by using NOMA.

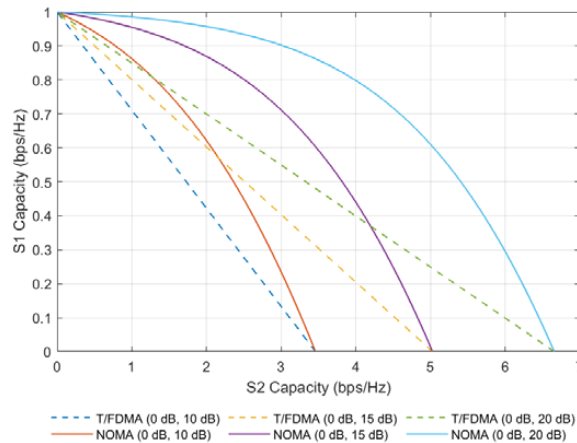


Fig. 2 Spectral efficiency comparison between NOMA and T/FDMA

2.2. RRM in 5G

The physical layer waveform of LTE is based on Orthogonal Frequency Division Multiplexing (OFDM). 5G follows the same principle. Nevertheless, one of the novelties of this standard is the flexibility of the PHY configuration. Five numerologies (μ) have been designed by varying the subcarrier spacing (SCS). The SCS value of each numerology can be obtained as follows:

$$SCS(kHz) = 15 \cdot 2^\mu, \quad (2)$$

where μ is the numerology and it can be 0, 1, 2, 3, or 4.

Concerning the frame structure, the length of the frames in 5G NR is set to 10 ms and they are composed of 10 consecutive subframes of one millisecond. Then, the slot number within a subframe varies depending on the numerology that is implemented. Table 1 describes the number of slots per subframe and their duration is described as a function of the numerology. These configuration choices of 5G NR are one of the main differences with LTE since those five different numerologies enable applications with different requirements. Moreover, depending on the used carrier frequency, the possible numerologies are limited: SCS of 15, 30, and 60 kHz are used below 6 GHz (i.e., frequency range 1, FR1), and 60 and 120 kHz SCSs are used above 6 GHz (i.e., frequency range 2, FR2) [40]. As described in Table 1, numerologies with high SCS imply short slot durations and, therefore, lower latencies could be achieved. This is the reason why, the highest numerologies (i.e., $\mu = 2$ below 6 GHz and $\mu = 3$ and $\mu = 4$ above 6 GHz) are more suitable for URLLC.

Table 1 5G NR frame components based on different numerologies [1]

μ	SCS (kHz)	# Slots/Subframe	Slot (ms)
0	15	1	1
1	30	2	0.5
2	60	4	0.25
3	120	8	0.125
4	240	16	0.0625

Regarding the number of OFDM symbols per slot, the same strategy as in LTE has been followed. In general, 14 symbols per slot is the default value in 5G NR, whereas some flexibility is also introduced in the symbol number. On the one hand, mini-slot configurations are available, where 2, 4, or 7 symbols can be used per slot. This configuration is designed to satisfy the requirements of applications where short data packets have to be delivered like in URLLC. On the contrary, especially for eMBB environments, several slots can be merged for long packet transmissions.

Another parameter affected by the flexibility of the numerologies is the OFDM symbol length. As presented in Table 2, the length of the OFDM symbol decreases while the SCS is increased. For the two highest numerologies, the duration of the OFDM symbol including the Cyclic Prefix (CP) is less than 10 μ s, and thus, it is a perfect fit for URLLC applications.

Table 2 OFDM symbol sizes in 5G [1]

	$\mu = 0$	$\mu = 1$	$\mu = 2$	$\mu = 3$	$\mu = 4$
OFDM Symbol (μ s)	66.67	33.33	16.67	8.33	4.17
CP (μ s)	4.69	2.34	1.17	0.57	0.29
Total length (μ s)	71.36	35.67	17.84	8.90	4.46

The resource allocation in 5G NR has also been modified in comparison with LTE. In this case, the smallest unit defined in the resource grid is the Resource Element (RE). RE is defined by one subcarrier and one OFDM symbol, in frequency and time domain, respectively [1]. Nevertheless, it is not possible to directly allocate RE, as in LTE, Resource Block (RB) are allocated, although there are not as in 4G. While in LTE one resource block was defined by 12 consecutive subcarriers in one slot (i.e., 7 OFDM symbols), in 5G NR, RBs are composed by one OFDM symbol in the time domain and 12 consecutive subcarriers in the frequency domain, corresponding to 180 kHz for 15 kHz SCS, 360 kHz for 30 kHz, and so forth [38]. Finally, in 5G NR, the maximum channel bandwidth is up to 100 MHz in FR1 and up to 400 MHz in FR2. In the second case, channels can be aggregated with a maximum bandwidth of 800 MHz.

3. Industrial use case

URLLC is a wide use case, where several types of applications are involved. One of the most relevant concepts and considered as the fourth industrial revolution is the so-called Industry 4.0 [13]. Industry 4.0 is leading the research and the advances to define and design the future industrial systems, including industrial communications. One of the main characteristics is the progressive deployment of wireless communications. Although wired connections are still commonly used in the industry due to their high

reliability, wireless systems offer an interesting improvement in scalability, cost reduction, and mobility that make them an ideal candidate for future industrial communication systems [44].

Several technologies and standards have been proposed towards a massive deployment of industrial wireless networks, such as IEEE 802.11 [43][42], Bluetooth [39], 802.15.4 [6], LTE [4], or WirelessHart [19]. However, none of those technologies can be considered the optimum solution for implementation in the industrial environment due to the strict characteristics and requirements involved. A detailed explanation of the strict requirements is provided in the following paragraphs.

One of the main challenges of industrial environments is the propagation channel. Metallic objects, machines in the industrial manufacturing plants, moving robots, etc. create a wireless propagation channel with a harsh multipath effect and a high access concurrence [10], which is hard to overcome. Such challenging channels cannot be overcome solely by physical layer techniques. Different MAC level techniques are required to complement the PHY performance, such as time division retransmissions [42][34] or spatial diversity techniques [25][23].

Industrial communications comprise different use cases with different requirements and characteristics. This paper addresses Factory Automation (FA), in which machines or complete systems require real-time control. Generally, FA represents production chains, where machines are the main elements of the process. Some examples of typical FA applications are assembly, packaging, palletizing, and manufacturing. These processes are critical and, therefore, require strict latency and reliability rates. In particular, cycle times are normally bounded between 0.25-10 ms, and a Packet Loss Rate (PLR) of 10^{-7} - 10^{-9} is required. Moreover, the update time for the devices of the network is between 0.5-50 ms. The size of the cells in FA implies a coverage range up to 100 meters and it is composed of up to 100 nodes. The data packet size is small in comparison with other use cases, normally, up to 300 Bytes, according to [41].

In a typical Industrial Wireless Sensor Network (IWSN), the nodes can be split into two groups: access points/gateways (AP) and sensor/control nodes. The AP node is the master node of the network. Among others, the main roles of the AP are network synchronization, collection of the sensed information by the sensors, and distribution of information and commands to the sensor nodes. On the other hand, sensor/control nodes are considered slave nodes that could have transceiver capacities. In general, they receive the information and the commands from the AP and they send back their sensed data within the cycle time [26].

The rest of the paper will consider a specific FA use case that involves three types of services. The first one is the transmission of Channel Quality Indicators (CQI)-based feedback from the nodes to the AP in an exclusive uplink channel. The second one is a broadcast service implemented from the AP to all the nodes in the network to deliver the critical information, such as synchronization, superframe starting signaling, and emergency alarms. It is important to highlight that the broadcast service is also used to deliver one of the widespread multimedia industrial applications: streaming video surveillance service. In this case, the objective of the broadcast service is to guarantee the safety of the workers and the live video-monitoring of the machines. The variable payload size of this service contains mission-critical information for a large number of nodes and it can be up to 300 Bytes. Then, the third one is a unicast service where the AP transmits a dedicated packet to each slave with the specific sensing commands and/or high-quality images/videos of the task that is carrying out. These packets (up to 64 Byte long) are also variable in payload size but contain less information than the broadcast packets. The main difference between the broadcast and the unicast services is the reliability requirement. While the proposed broadcast service is considered mission-critical, the unicast service is a non-critical and loss and delay-tolerant service (i.e., also known as Best Effort service). In order to deploy both multimedia video services, broadcast and unicast, a capacity of hundreds of kbps or a few Mbps per device has to be guaranteed according to the Monitoring & Diagnostic use case defined in [35].

The wireless modeling will be based on the proposals made by the 802.15.4 standardization groups [32] and the experiments carried out on [12]. Specifically, the so-called Channel Model 7 (CM7), with a coherence time (T_{Coh}) of 30 ms has been selected. Up to 100 nodes are assumed randomly distributed through the cell, with the AP installed in an optimal position in the middle of the hall, where Line-of-Sight (LOS) conditions dominate. The system is based on a 10/20 MHz channel bandwidth in the 2.4 GHz ISM band, -90dBm is the thermal noise power and the transmitted power is set to 10 dBm. The rest of the network parameters are summarized in Table 3.

Table 3 Network parameters of the industrial use case

Parameter	Value
Application	FA
Dimensions	80 x 40 m
# Nodes	Up to 100
Broadcast payload	Up to 300 Byte
Unicast payload	Up to 64 Byte
Channel Model	CM7
Shadowing	$\mu = 0$ $\sigma = 6$ dB
Bandwidth	10/20 MHz
Frequency	2.4 GHz
SCS	60 kHz
Thermal Noise	-90 dBm
T_{Cycle}	Up to 5 ms
Tx Power	10 dBm
T_{Coh}	30 ms

4. RRM algorithm

In this scenario, the AP performs the role of a Next Generation NodeB (gNB) and delivers the information with different requirements and characteristics to the nodes integrated into the network. The information flow goes from the AP to each of the nodes in the network. Therefore, as it is a downlink communication network, the Physical Downlink Shared Channel (PDSCH) has been used. In this section, there are presented different RRM algorithms with different optimization goals for both TDMA and NOMA. The algorithms presented in this section distribute the available RBs between the broadcast services and the dedicated unicast services.

4.1. RRM management using TDMA

In this first approach, TDMA is used as the multiplexing technology for conveying broadcast and unicast services simultaneously. A summary of the designed RRM algorithm for TDMA is shown in Algorithm 1 and a detailed explanation of each step is presented below.

Algorithm 1: TDMA-based RRM algorithm (I)
Step 1: Receive CQI feedback from the users.
Step 2: Calculate the available RBs.
Step 3: Configure the broadcast service.
for $r > 0$
Step 4: Configure the unicast service of one user and update the amount of available RBs.
end for

First, in Step 1, the AP collects the CQIs that each device has transmitted in the PUCCH (Physical Uplink Control Channel). Each user informs the AP with the CQI, which is the maximum Modulation and Code Scheme (MCS) that could correctly decode from the possible values presented in Table 5.1.3.1-2 in [3] according to its instantaneous SNR value.

Then, Step 2 is in charge of calculating the amount of RBs that are available for sharing among the users. Eq. (3) will be used to obtain N_{RB} :

$$N_{RB} = BW \cdot N_{\text{Symbols}} \cdot N_{\text{Slots}} \quad (3)$$

where N_{RB} is the total amount of available RBs, BW is the number of RBs forming the channel bandwidth (e.g., 25 RBs for a 20 MHz channel), N_{Symbols} is the number of symbols in a time slot (i.e., 14 symbols) and N_{Slots} is the number of slots gathered for the RRM management. The calculation of the total number of slots is based on the acceptable maximum cycle time (T_{Cycle}). Taking into account that using 60 kHz as SCS the duration of a time slot is 0.25 ms (see Table 1), the number of time slots used for each iteration of the RRM algorithm is calculated as follows:

$$N_{\text{slots}} = \frac{T_{\text{cycle}}}{0.25} \quad (4)$$

where T_{cycle} is expressed in ms.

Once, the amount of available RBs is calculated, the broadcast service is configured in Step 3. Taking into account that the broadcast service is critical with mandatory reliability requirements, the lowest MCS in Table 5.1.3.1-2 in [3] is used. Then, the amount of RBs that have to be allocated for the broadcast service is calculated in two steps. First, the required number of subcarriers is calculated as follows:

$$\text{Subcarriers}_{\text{Br}} = \frac{\text{Payload Size}_{\text{Br}}}{\text{Efficiency MCS0}} \quad (5)$$

where the $\text{Payload Size}_{\text{Br}}$ is expressed in bits and the Efficiency MCS0 , as defined in Table 5.1.3.1-2 in [3], is 0.2344 bps/Hz. Then, the number of RBs is calculated based on $\text{Subcarriers}_{\text{Br}}$ as follows:

$$\text{RB}_{\text{Br}} = \text{round}\left(\frac{\text{Subcarriers}_{\text{Br}}}{12}\right) \quad (6)$$

where 12 represents the number of subcarriers within an RB and the round function is used to obtain the next integer value of the division result. After obtaining the number of RBs allocated to the broadcast service, the value is subtracted from the total number of available RBs:

$$r = N_{\text{RB}} - \text{RB}_{\text{Br}} \quad (7)$$

Then, before configuring any unicast services, it has to be checked if there are still available RBs to allocate (i.e., $r > 0$). If the statement is true, the first unicast user is configured in Step 4 by calculating the RBs allocated to the first unicast user. The set of unicast users can be expressed as $U = \{u_1, u_2, \dots, u_N\}$. This algorithm is oriented to maximize the network capacity or the number of served users, so, the users with the highest requested MCS values are served first since they will require a small portion of the available bandwidth. Therefore, as in Eq. (5), first, the number of subcarriers allocated to the first user is calculated:

$$\text{Subcarriers}_{u_1} = \frac{\text{Payload Size}_{u_1}}{\text{Efficiency}_{u_1}} \quad (8)$$

In this case, Efficiency_{u_1} is the efficiency related to the MCS requested by u_1 . Then, the amount of RBs dedicated to u_1 are calculated as in Eq. (6):

$$\text{RB}_{u_1} = \text{round}\left(\frac{\text{Subcarriers}_{u_1}}{12}\right) \quad (9)$$

After that, the amount of available RBs is updated by subtracting RB_{u_1} :

$$r = r - \text{RB}_{u_1} \quad (10)$$

If the amount of allocable RBs is positive (i.e., $r > 0$), the next unicast user is configured following Eq. (8) and Eq. (9) to calculate the amount of dedicated RBs and the available RBs (i.e., r) is updated again as in Eq. (10). This looping process is executed until all the RBs in N_{RB} are allocated. If all the users forming the network have been served and there are still RBs to allocate, users are served again in order to increase the network capacity and reliability.

Algorithm 1 implies that the T_{cycle} is fixed and the number of users served varies depending on the input parameters. In order to provide a different perspective, another algorithm has been developed, where the number of users that have to be served is fixed and the required T_{cycle} to serve all of them is calculated. A summary of the second RRM algorithm is presented in Algorithm 2 and an in-depth analysis of each step is provided below.

Algorithm 2: TDMA-based RRM algorithm (II)

Step 1: Receive CQI feedback from the users.
 Step 2: Configure the broadcast service and calculate the required RBs.
 for $n \leq N$
 Step 3: Configure the unicast service of the user u_N
 and update the amount of required RBs.
 end for
 Step 4: Calculate the required T_{Cycle} .

The starting point is again the reception of the CQI feedback of each user from the PUCCH channel. In this case, the AP has to manage the RBs that are necessary to offer the whole set of users (i.e., $U = \{u_1, u_2, \dots, u_N\}$) the critical broadcast service and the non-critical unicast services. Then, in Step 2, the broadcast service is configured by using the most robust MCS value available and the required amount of RBs (i.e., RB_{Br}) is calculated following Eq. (5) and Eq. (6).

When the broadcast service is configured, unicast services are individually configured. In this case, it is mandatory that all the users have to be served. In consequence, there is no preference in the serving order for users with high MCS. To configure each unicast service and calculate the required amount of RBs (i.e., RB_{u_n}), as in Algorithm 1, Eq. (8) and Eq. (9) are followed.

Once the allocation of RBs for each unicast user is carried out, the required T_{Cycle} is estimated. First, the total amount of RBs required to offer broadcast and unicast services (i.e., RB_{Total}) is calculated as follows:

$$RB_{\text{Total}} = RB_{Br} + RB_{u_1} + RB_{u_2} + \dots + RB_{u_N} \quad (11)$$

Then, the number of slots required to organize RB_{Total} is calculated from Eq. (3) and, finally, taking into account the duration of each slot (see Table 1), the required T_{Cycle} is calculated from Eq. (4).

4.2. RRM management using NOMA

In this section, two algorithms are presented in order to manage the RRM of 5G NR using NOMA. In this case, the broadcast service is delivered in the Upper Layer (UL) of the NOMA signal, in order to provide high reliability, and the unicast services, as they are considered non-critical, are transmitted in the Lower Layer (LL). A summary of the first algorithm is presented in Algorithm 3, where as in Algorithm 1, the maximum T_{Cycle} is fixed.

Algorithm 3: NOMA-based RRM algorithm (I)

Step 1: Receive CQI feedback from the users.
 Step 2: Calculate the available RBs.
 Step 3: Configure the set of possible Δ values.
 for $m \leq M$
 Step 4: Configure the broadcast service
 for $r > 0$
 Step 5: Configure the unicast services of
 one user and update the amount of available
 RBs.
 end for
 end for
 Step 6: Select the optimum solution

The first two steps of the NOMA-based algorithm are the same as in Algorithm 1, that is, the CQI feedback from the users is received in the PUCCH channel and the amount of RBs that are available for sharing among the users (i.e., N_{RB}) is calculated.

Then, in Step 3 the set of possible Δ values is defined as $\Delta = \{\Delta_1, \Delta_2, \dots, \Delta_M\}$. In order to define the set of values, the maximum assumable degradation in the UL of NOMA (γ) has to be managed. γ represents the maximum SNR difference between the most robust configuration using and not using NOMA and it can be calculated with the following expression:

$$\gamma < SNR_{MCS0_{UL}} - SNR_{MCS0_{SL}} \quad (12)$$

γ implies a tradeoff between reliability and capacity. In fact, the closer is γ to zero, the more similar are the performance of UL and broadcast service in TDMA (see the previous section). However, in order to achieve γ close to zero, high Δ values are required and those cases suppose a considerable reduction in the capacity delivered by the LL. Therefore, a balance has to be sought between the acceptable reliability losses in the UL in exchange for the capacity performance of the LL. Once, γ and $SNR_{MCS0_{UL}}$ are defined, the minimum value of Δ that guarantees that γ is accomplished is searched starting from $\Delta = 0$ dB and with steps of 0.5 dB. Then, the set of possible Δ values is completed with values up to $\Delta = -20$ dB and steps of 0.5 dB.

Afterward, an iterative process starts in order to test the RRM performance of each value in Δ . First, the broadcast service is configured, which is delivered in the UL 100% of the time in the whole RF bandwidth. The broadcast service is configured with the lowest MCS value available in Table 5.1.3.1-2 in [3].

Once the broadcast service is defined, the same process as in the case of Algorithm 1 is performed, where unicast users are individually served until all the available RBs (i.e., $r = 0$) are allocated. Then, the configuration of the users is saved and the next value in the set of possible injection levels is tested.

When all the possible values in Δ are evaluated the best solution has to be selected. To do so, different rules could be applied, in this work, two are going to be evaluated: the solution that maximizes the capacity of the unicast services and the solution that maximizes the number of served unicast users. This is one of the main differences in comparison with the TDMA-based algorithm. While the RB management cannot be optimized in TDMA since, there is one possible configuration under the predefined conditions, using NOMA several configurations are possible under the same conditions and the best performing one can be selected.

As in TDMA, another version of the NOMA-based RRM algorithm has been developed, where the goal of the algorithm is to find the minimum T_{Cycle} for a fixed number of unicast users. A summary of the second algorithm is presented in Algorithm 4 and an in-depth analysis of each step is provided below.

Algorithm 4: NOMA-based RRM algorithm (II)

Step 1: Receive CQI feedback from the users.
Step 2: Configure the set of possible Δ values.
for $m \leq M$
 Step 3: Configure the broadcast service and calculate the required RBs.
 for $n \leq N$
 Step 4: Configure the unicast service of the user u_n and update the amount of required RBs.
 end for
 Step 5: Calculate the required T_{Cycle} .
end for
Step 6: Select the optimum solution

This second algorithm starts similar to Algorithm 1 since first, the CQI feedbacks are collected forming the set of users ($U = \{u_1, u_2, \dots, u_N\}$) and in a second step the set of possible injection levels ($\Delta = \{\Delta_1, \Delta_2, \dots, \Delta_M\}$) is calculated according to the maximum assumable degradation in the UL of NOMA (γ). Then, an iterative loop is started to evaluate each possible injection level value.

The first step in the iterative loop is to configure the critical broadcast service and calculate the required amount of RBs (i.e., RB_{Br}). To do so, as in TDMA, Eq. (5) and Eq. (6) are followed by using the most robust configuration in order to ensure a high-reliability rate. After that, each user in the set of users is managed and the required amount of RBs (i.e., RB_{u_n}) is calculated following Eq. (8) and Eq. (9). In contrast to Algorithm 2, in this case, the number of required RBs are separately aggregated depending on the type of service. Therefore, the total amount of RBs required to manage all the unicast services is calculated:

$$RB_{Uni} = RB_{u_1} + RB_{u_2} + \dots + RB_{u_N} \quad (13)$$

Then, the corresponding T_{Cycle} for each value in the set of possible injection levels is calculated in Step 5. In this case, taking into account the characteristics of NOMA, the number of RBs allocated for the broadcast services (i.e., RB_{Br}) are exclusively used in the UL, while the number of RBs allocated for the unicast services (i.e., RB_{Uni}) are used in the LL. Therefore, the total amount of required RBs is no longer obtained by adding both values, but it is defined by the maximum of both values:

$$RB_{Total} = \max(RB_{Br}, RB_{Uni}) \quad (14)$$

Once the required amount of RBs is calculated, the process as in TDMA is followed: first, the number of slots is calculated from Eq. (3) and, second, the required T_{Cycle} is calculated from Eq. (4).

Finally, when all the values in Δ are analyzed, the best solution is chosen in Step 6 by selecting the one implying the lowest T_{Cycle} value.

5. Results

This section presents and compares the results obtained by executing the algorithms of section 4 in the use case described in section 3.

5.1. Capacity analysis

First, the capacity obtained by using Algorithm 1 and Algorithm 3 is compared. The comparison will be performed by first finding the configuration that maximizes the capacity of the unicast services. The evaluation will be based on three capacity metrics: the throughput of the broadcast service, the Aggregate Data Rate of the unicast services, and the total ADR.

Firstly, the throughput obtained for the broadcast service (Th_{Br}) is shown in Fig. 3 for different T_{Cycle} values. In this case, the payload of the broadcast packet is 100 Bytes and the network is composed by 100 devices. It is important to highlight, that NOMA-based RRM outperforms TDMA with higher capacity values. What is more, the difference between technologies increases as the T_{Cycle} increases. In fact, the maximum gain case appears for one millisecond T_{Cycle} , where NOMA offers a gain of 3.36 Mbps in the 20 MHz channel (1.33 Mbps in the 10 MHz channel). On the other hand, the maximum assumable SNR degradation (γ) does not modify the results of the broadcast capacity since the parameter affected is the availability of the broadcast service, which represents the ratio between the number of correctly served users and the total number of users. In this case, very similar availability values are obtained in all the cases. In fact, although the highest availability value is obtained in the TDMA case with 0.999812, NOMA configurations offer very similar performance: 0.999707 for $\gamma = 0.5$ dB and 0.999611 for $\gamma = 1$ dB. Finally, it should also be highlighted that NOMA offers a constant capacity value even if the T_{Cycle} value is modified, whereas TDMA offers variable capacity. In fact, the constant capacity achieved by NOMA is the maximum achievable capacity for the MCS0. Moreover, the capacity variation of TDMA is due to the RB sharing between broadcast and unicast services. Once the predefined broadcast payload has been managed, RBs are allocated for unicast services, and, therefore, the more RBs are allocated for unicast services, the lower is the broadcast capacity. Based on the broadcast service throughput results obtained and taking into account that the throughput ranges between 1.43 Mbps and 4.22 Mbps, the broadcast service could correctly address the transmission of video streaming content, as established in [35]. Furthermore, based on Fig. 3, the throughput obtained when NOMA is used in the 20 MHz channel could be used for higher quality services such as 4k content to receivers on small screens (displays, mobiles devices).

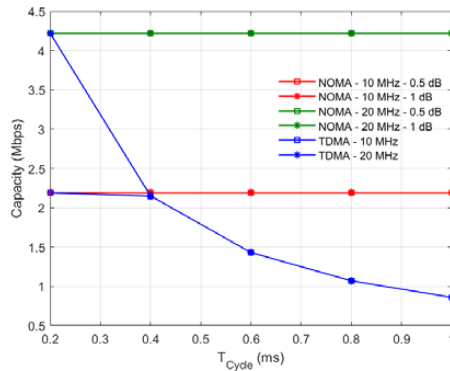


Fig. 3 Broadcast service throughput (Th_{Br}) for different T_{Cycle} values

Afterward, the ADR of the unicast services (ADR_{Un}) is shown in Fig. 4, calculated as the sum of the capacities obtained by serving all the possible unicast communications in the network within a specific T_{Cycle} (i.e., up to 100 devices). In this case, in order to consider a device served, 32 Bytes have to be delivered. Unicast level results are more variable than the results obtained for the broadcast services. First, the best technology for the proposed cases is affected by the channel bandwidth. In general, NOMA is better in the small bandwidth channel (i.e., 10 MHz) and TDMA performs better when the bandwidth is increased (i.e., 20 MHz). However, a positive aspect of NOMA configurations is that always is able to offer the capacity to the unicast devices, while, on the contrary, TDMA does not, as it can be seen in the lowest T_{Cycle} values. As opposed to the broadcast throughput, variations on the maximum assumable SNR degradation (γ) have direct effect on the unicast service capacity. In particular, the capacity performance when $\gamma = 0.5$ dB is assumed is considerably worsen in comparison with $\gamma = 1$ dB. Based on the unicast ADR results shown in Fig. 4, although high throughput values are obtained (close to 90 Mbps), the throughput per node ratio ranges between 1-0.5 Mbps/node since as will be shown in the next subsection, not all the unicast devices are served. This throughput rate will be enough to offer a standard quality video streaming service or high definition images, as established in [35]. In addition, it should be noted that this service will have assumable latency values (cycle time values below one ms). Then, if images or video content with higher definition are required (high challenging multimedia services), some network parameters could be modified such as reducing the number of nodes or increasing the bandwidth without any negative impact on the overall performance.

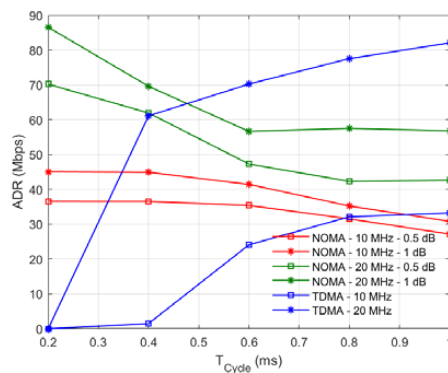


Fig. 4 Unicast service ADR (ADR_{Un}) for different T_{Cycle} values

Once broadcast and unicast services capacity performance has been evaluated, the combined ADR is presented in Fig. 5, as the sum of all the received capacities, broadcast and unicast, within a specific T_{Cycle} value. The same parameters as in the previous case have been used. These results present NOMA as a relevant candidate for RRM managing algorithms since it provides a considerable increase in the total ADR

of the network. In fact, again, the best cases are located in $T_{\text{Cycle}} = 1$ ms, where NOMA is close to triplicate and to duplicate the ADR of TDMA in the 20 MHz and 10 MHz channel, respectively. In consequence, taking into account that the same number of resources has been share in NOMA and TDMA, NOMA demonstrates that is a highly spectrum efficient technique.

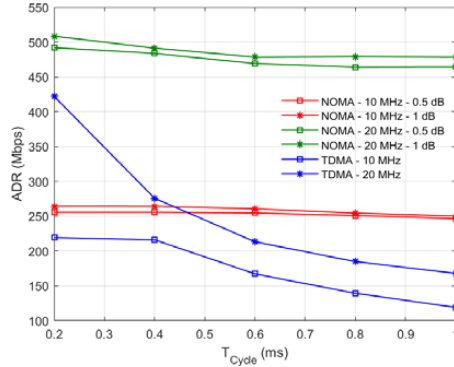


Fig. 5 Total ADR for different T_{Cycle} values

In addition to the T_{Cycle} -based analysis, capacity performance can also be analyzed from the payload size perspective. First, the impact of the broadcast service packet size is summarized in Table 4. In this case, an intermediate case has been selected: T_{Cycle} of 0.6 ms and up to 1 dB of SNR degradation for NOMA configurations. Results show that the payload of the broadcast service does not affect the RRM management of NOMA since the same results are obtained for each metric. However, TDMA is affected by the broadcast service packet size. When the payload of the broadcast services increases, the throughput of the broadcast content increases, and the ADR of the unicast services decreases. In particular, when the 10 MHz channel is used and the broadcast payload is incremented to 200 Bytes, there are no available RBs to manage the unicast services and, therefore, no capacity can be achieved for the unicast devices.

Table 4 Impact of the broadcast service packet size on the capacity

	10 MHz				20 MHz			
	NOMA		TDMA		NOMA		TDMA	
	100 B	200 B	100 B	200 B	100 B	200 B	100 B	200 B
Th_{Br} (Mbps)	2.19	2.19	1.43	2.19	4.22	4.22	1.43	2.86
ADR_{Un} (Mbps)	41.44	41.44	24.09	0.00	56.64	56.64	70.24	40.35
ADR (Mbps)	260.76	260.76	167.21	219.36	478.40	478.40	213.37	326.09

Finally, by using the same parameter configuration, the impact of the unicast service packet size on the capacity is shown in Table 5. From the capacity perspective, an increment of the unicast packet size involves an increment on the unicast ADR for both technologies, while the throughput of the broadcast services remains constant since unicast services are configured after the broadcast content configuration. Although the increase is more evident in the 20 MHz channel, in the case of the 10 MHz channel the capacity also increases. In particular, the performance of TDMA in the 10 MHz channel is almost constant since the increment in the payload size is compensated with an equivalent decrease in the number of served unicast users.

Table 5 Impact of the unicast service packet size on the capacity

	10 MHz				20 MHz			
	NOMA		TDMA		NOMA		TDMA	
	32 B	64 B	32 B	64 B	32 B	64 B	32 B	64 B
Th_{Br} (Mbps)	2.19	2.19	1.43	1.43	4.22	4.22	1.43	1.43
ADR_{Un} (Mbps)	41.44	45.07	24.09	24.12	56.64	77.65	70.24	81.61
ADR (Mbps)	260.76	264.38	167.21	167.24	478.40	499.41	213.37	224.74

5.2. Analysis of the number of users

This subsection compares the performance of TDMA and NOMA in the RRM layer in terms of the number of unicast users served. First, the evolution of the served unicast users for different T_{Cycle} values is shown

in Fig. 6. In general, these curves show two parts: the fast increment and the stabilization. As it is shown in the figure, TDMA shows a fast behavior and arrives in the stabilization phase faster than NOMA. However, as in Fig. 4, not all the configurations are useful since in some cases, TDMA is not able to offer unicast services. Concerning NOMA, the maximum assumable SNR degradation (γ) is also critical in this analysis since the higher is γ , the higher is the number of served users. In order to enhance the comparison, if the benchmark is set in 90% of unicast users served, the best RRM algorithm is NOMA with $\gamma = 1$ dB (i.e., 0.4 ms and 0.76 ms are required for 20 MHz and 10 MHz channel bandwidths, respectively) and TDMA performs better than NOMA with $\gamma = 0.5$ dB. However, if more strict benchmarks are set, results may vary in favor of TDMA.

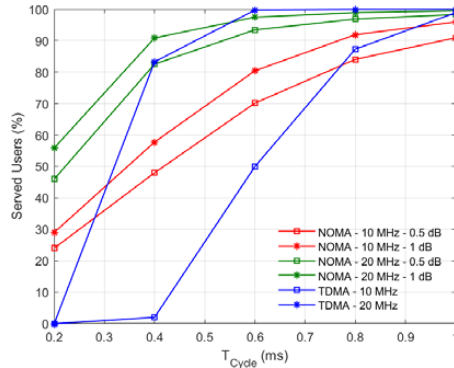


Fig. 6 Served unicast users for different T_{Cycle} values

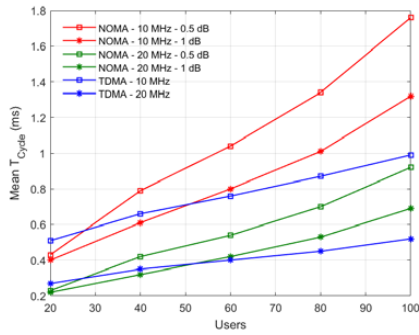
Then, the analysis of the number of users served can go deeper by taking into account the influence of the payload of the broadcast and unicast services (See Table 6). To do so, an intermediate set of parameters has been selected, where T_{Cycle} is 0.6 ms and up to 1 dB of SNR degradation for NOMA is acceptable. In general, the number of users served with TDMA is more dependent on the payload sizes than in the case of NOMA. In particular, the results obtained with NOMA are only affected by the payload of the unicast content. Table 6 shows that the performance obtained with NOMA remains constant no matter the size of the broadcast service packet size. On the other hand, TDMA results are affected by both payload sizes, broadcast, and unicast payloads. In addition, the number of unicast users served decreases considerably fast, while the packet sizes are increased. In fact, in half of the cases, there are not enough resources to offer unicast services, making NOMA a better candidate to guarantee a minimum number of unicast services.

Table 6 Impact of the packet size on the number of served users (%)

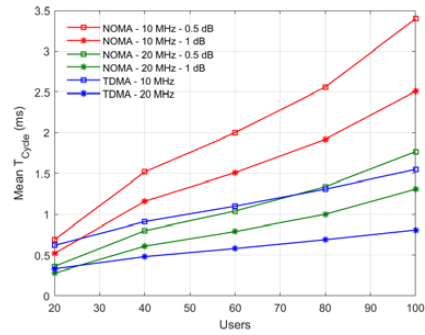
Broadcast packet size	100 B		200 B		300 B	
Unicast packet size	32 B	64 B	32 B	64 B	32 B	64 B
NOMA - 10 MHz	80.45	47.98	80.45	47.98	80.45	47.98
TDMA - 10 MHz	49.98	25.00	0.00	0.00	0.00	0.00
NOMA - 20 MHz	97.47	82.85	97.47	82.85	97.47	82.85
TDMA - 20 MHz	99.76	84.83	82.46	44.99	0.00	0.00

5.3. Cycle time duration analysis

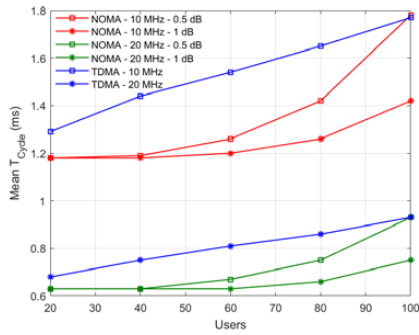
Finally, the T_{Cycle} is used in this subsection as a metric to describe how fast can Algorithm 2 and Algorithm 4 manage all the users in the network. The number of users that compound the network and that have to be mandatorily served is varied to obtain cycle time measurements under different conditions. Fig. 7 shows the mean minimum T_{Cycle} for different broadcast and unicast payload sizes. In general, there is not a clear winning technology and the selection of the best performing multiplexing technology depends on the parameter configuration. For example, an increment in the broadcast payload involves a better performance of NOMA, while increasing the unicast packet size TDMA outperforms NOMA. Regarding the number of users in the network, TDMA performs better in very dense configurations, while NOMA provides lower T_{Cycle} values when the network is not so crowded. In any case, all the simulations carried out in this section with different parameter configurations guarantee that the minimum T_{Cycle} value specified for FA environments (i.e., below 10 ms) is accomplished.



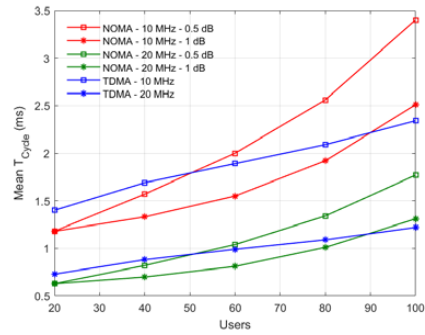
(a) Broadcast packet size 100 B and unicast packet size 32 B



(b) Broadcast packet size 100 B and unicast packet size 64 B



(c) Broadcast packet size 300 B and unicast packet size 32 B



(d) Broadcast packet size 300 B and unicast packet size 64 B

Fig. 7 Mean T_{Cycle} values varying the number of users for different configurations.

5.4. Result summary

The objective of this subsection is to summarize the obtained results in previous sections and to select the most suitable multiplexing technique according to the already evaluated parameters. Table 7 summarizes results by highlighting the best performing multiplexing technique in relation to different parameter ranges. In general, although there are several ranges where similar performance is obtained with both techniques, NOMA is the best technique in more ranges. In particular, NOMA offers better performance for achieving the first two goals (i.e., maximize capacity and maximize served users), while in the case of minimizing the T_{Cycle} there is not a clear winning technique. It is also important to point out that there are cases, where it is not evident to decide which multiplexing technique performs better because there is another more critical parameter. For example, in the case of minimizing the T_{Cycle} the channel bandwidth is not a critical factor since the payload of the broadcast service is more critical and determines which the best performing alternative is. On the other hand, it is also hard to determine the best multiplexing technique when the goal is to maximize the capacity since, as shown in section 5.1, there is not a single metric. For instance, in the range of broadcast payload ≤ 100 Byte both technologies are selected because NOMA performs better in the broadcast throughput and the total ADR, whereas TDMA offers better results in the unicast ADR metric.

Table 7 Selection of the best performing multiplexing technique according to different parameters and optimization goals

Goal	Parameter	Range	Best Performant Technique
Maximize capacity	Broadcast payload	≤ 100 Byte	TDMA/NOMA
		> 100 Byte	NOMA
	Unicast payload	≤ 32 Byte	TDMA/NOMA
		> 32 Byte	TDMA/NOMA
	T_{Cycle}	≤ 0.5 ms	TDMA/NOMA
		> 0.5 ms	NOMA
BW	≤ 10 MHz	NOMA	
	> 10 MHz	TDMA/NOMA	
Maximize served users	Broadcast payload	≤ 100 Byte	TDMA/NOMA
		> 100 Byte	NOMA
	Unicast payload	≤ 32 Byte	TDMA/NOMA
		> 32 Byte	TDMA/NOMA
	T_{Cycle}	≤ 0.5 ms	NOMA
		> 0.5 ms	TDMA
BW	≤ 10 MHz	NOMA	
	> 10 MHz	TDMA/NOMA	
Minimize T_{Cycle}	Broadcast payload	≤ 100 Byte	TDMA
		> 100 Byte	NOMA
	Unicast payload	≤ 32 Byte	TDMA/NOMA
		> 32 Byte	TDMA/NOMA
	Number of users	≤ 40	NOMA
		> 40	TDMA
BW	≤ 10 MHz	TDMA/NOMA	
	> 10 MHz	TDMA/NOMA	

6. Conclusions

In this paper, the use of P-NOMA to manage the resource allocation layer has been proposed and evaluated using different RRM algorithms. In addition, the resource allocation and the obtained results have been compared with TDMA. In order to make a fair comparison, different affecting parameters have been identified and several RRM algorithms have been designed according to different optimization goals. Results indicate that there is not a clear winning multiplexing technology and the most suitable election totally depends on the network parameters. However, NOMA techniques are the most suitable option when the optimization goal is to maximize the network capacity or the amount of served unicast users.

This work opens the door to several future research avenues. On the one hand, the analysis presented in this paper could go deeper by carrying out more simulations in order to widen the ranges of each parameter or in different FA environments to confirm or adapt the parameter ranges provided in this paper. Moreover, different RRM algorithms could be designed with combined optimization goals, such as availability and capacity simultaneously. On the other hand, a solution based on the combination of NOMA and T/FDMA techniques could be sought in order to improve the spectral efficiency and to distribute better the gain of NOMA between broadcast and unicast services. This solution, theoretically, should increment the granularity of the configuring options and, therefore, the best performing solution for each case could be achieved. Finally, this kind of RRM solution could be combined with a 5G NR PHY/MAC level transceiver to simulate other aspects of a 5G-based communication system. In addition to the metrics used in this work (i.e., ADR or T_{Cycle}), metrics related to the PHY and the MAC layers could be used, such as user plane latency or Packet Error Rate (PER).

Acknowledgments

This work was supported in part by the Basque Government (Project IOTERRAZ) under Grant KK-2019/00046 ELKARTEK 2019, Grant IT1234-19, and the PREDOC Grant Program PRE_2020_2_0105, and in part by the Spanish Government (Project PHANTOM) under Grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE).

References

- [1] 3GPP TR 38.802 V14.2.0 (2017) Study on New Radio (NR) Access Technology Physical Layer Aspects, 3rd Generation Partnership Project. Tech Rep.
- [2] 3GPP TS 38.201 V15.0.0 (2018) NR; Physical Layer; General Description, 3rd Generation Partnership Project. Tech Spec.
- [3] 3GPP TS 38.214 v15.3.0 (2018) NR; Physical layer procedures for data (Release15), 3rd Generation Partnership Project. Tech Rep.
- [4] Aktas I et al (2017) LTE evolution—Latency reduction and reliability enhancements for wireless industrial automation. 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), IEEE, Montreal, pp. 1-7. <https://doi.org/10.1109/PIMRC.2017.8292603>
- [5] Al-Turjman, F., Alturjman, S. 5G/IoT-enabled UAVs for multimedia delivery in industry-oriented applications. *Multimed Tools Appl* 79, 8627–8648 (2020). <https://doi.org/10.1007/s11042-018-6288-7>.
- [6] Anwar M, Xia Y, Zhan Y (2016) TDMA-Based IEEE 802.15.4 for Low-Latency Deterministic Control Applications. *IEEE Transactions on Industrial Informatics* 12(1): 338-347. <https://doi.org/10.1109/TII.2015.2508719>
- [7] Ao W, Cui Y, Yao Q, Li X (2019) Design and Implementation of Distributed Video Equipment Monitoring and Management System. *IEEE International Conference on Industrial Internet (ICII)*, IEEE, Orlando, pp. 423-427. <https://doi.org/10.1109/ICII.2019.00078>
- [8] Bergmans P, Cover T (1974) Cooperative broadcasting. *IEEE Transactions on Information Theory* 20(3): 317–324. <https://doi.org/10.1109/TIT.1974.1055232>
- [9] Blanco-Novoa O, Fernández-Caramés TM, Fraga-Lamas P, Vilar-Montesinos MA (2018) A Practical Evaluation of Commercial Industrial Augmented Reality Systems in an Industry 4.0 Shipyard. *IEEE Access* 6:8201-8218. <https://doi.org/10.1109/ACCESS.2018.2802699>
- [10] Coll JF, Chilo J, Slimane B (2012). Radio-frequency electromagnetic characterization in factory infrastructures. *IEEE Transactions on Electromagnetic Compatibility* 54(3): 708-711. <https://doi.org/10.1109/TEMC.2012.2197753>
- [11] Cover T (1972) Broadcast channels. *IEEE Transactions on Information Theory* 18(1): 2–14. <https://doi.org/10.1109/TIT.1972.1054727>
- [12] Croonenbroeck R, Underberg L, Wulf A, Kays R (2017) Measurements for the development of an enhanced model for wireless channels in industrial environments. 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), IEEE, Rome, pp. 1-8. <https://doi.org/10.1109/WiMOB.2017.8115764>
- [13] Drath R, Horch A (2014) Industrie 4.0: Hit or Hype? [Industry Forum]. *IEEE Industrial Electronics Magazine* 8(2): 56-58. <https://doi.org/10.1109/MIE.2014.2312079>
- [14] Egger-Lampl S, Gerdenitsch C, Deinhard L, Schatz R, Hold P (2019) Assembly Instructions with AR: Towards measuring Interactive Assistance Experience in an Industry 4.0 Context. Eleventh International Conference on Quality of Multimedia Experience (QoMEX), IEEE, Berlin, pp. 1-3. <https://doi.org/10.1109/QoMEX.2019.8743266>
- [15] Fraga-Lamas P, Fernández-Caramés TM, Blanco-Novoa O, Vilar-Montesinos MA (2018) A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. *IEEE Access* 6:13358-13375. <https://doi.org/10.1109/ACCESS.2018.2808326>
- [16] Ghini V, Casadei M, Borgo FD, Vincenzi N, Prandi C, Mirri S (2019) Industry 4.0 and Video Monitoring: a Multidimensional Approach Based on MPEG-DASH. 16th IEEE Annual Consumer Communications & Networking Conference (CCNC), IEEE, Las Vegas, pp. 1-6. <https://doi.org/10.1109/CCNC.2019.8651683>
- [17] Gong L, Fast-Berglund A, Johansson B (2021) A Framework for Extended Reality System Development in Manufacturing. *IEEE Access* 9:24796-24813. <https://doi.org/10.1109/ACCESS.2021.3056752>
- [18] Gosh A, Maeder A, Baker M, Chandramouli D (2019) 5G evolution: View on 5G cellular technology beyond 3GPP release 15. *IEEE Access* 7:127639 - 127651. <https://doi.org/10.1109/ACCESS.2019.2939938>
- [19] Hassan SM, Ibrahim R, Bingi K, Chung TD, Saad N (2017) Application of wireless technology for control: A WirelessHART perspective. *Procedia Computer Science* 105(supplement C): 240-247. <https://doi.org/10.1016/j.procs.2017.01.217>
- [20] Hoshyar R, Wathan FP, Tafazolli R (2008) Novel low-density signature for synchronous CDMA systems over AWGN channel. *IEEE Transactions on Signal Processing* 56(4):1616–1626. <https://doi.org/10.1109/TSP.2007.909320>
- [21] Hsu C, Kang L, You T, Zhong W (2017) Vision-Based Automatic Identification Tracking of Steel Products for Intelligent Steel Manufacturing. *IEEE International Symposium on Multimedia (ISM)*, IEEE, Taichung, pp. 376-377. <https://doi.org/10.1109/ISM.2017.75>
- [22] Iradier E et al (2020) Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks. *IEEE Transactions on Broadcasting*. <https://doi.org/10.1109/TBC.2020.2981759>

- [23] Iradier E et al (2021) Analysis of NOMA-Based Retransmission Schemes for Factory Automation Applications. *IEEE Access* 9:29541-29554. <https://doi.org/10.1109/ACCESS.2021.3059069>
- [24] Iradier E, Montalban J, Araniti G, Fadda M, Murrioni M (2016) Adaptive resource allocation in LTE vehicular services using LDM. *International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, IEEE, Nara, pp. 1-3. <https://doi.org/10.1109/BMSB.2016.7521985>
- [25] Iradier E, Montalban J, Fanari L, Angueira P (2019) On the Use of Spatial Diversity under Highly Challenging Channels for Ultra Reliable Communications. *24th International Conference on Emerging Technologies and Factory Automation (ETFA)*, IEEE, Zaragoza, pp. 200-207. <https://doi.org/10.1109/ETFA.2019.8869055>
- [26] Iradier E, Montalban J, Fanari L, Angueira P, Seijo O, Val I (2019) NOMA-based 802.11n for Broadcasting Multimedia Content in Factory Automation Environments. *International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, IEEE, Jeju, pp. 1-6. <https://doi.org/10.1109/10.1109/BMSB47279.2019.8971844>
- [27] Iradier E, Montalban J, Romero D, Wu Y, Zhang L, Li W (2019) NOMA based 5G NR for PTM Communications. *International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, IEEE, Jeju, pp. 1-6. <https://doi.org/10.1109/BMSB47279.2019.8971856>
- [28] Islam SMR, Avazov N, Dobre OA, Kwak K (2017) Power Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges. *IEEE Communications Surveys & Tutorials* 19(2): 721-742. <https://doi.org/10.1109/COMST.2016.2621116>
- [29] Kumar, M., Tripathi, R. & Tiwari, S. QoS guarantee towards reliability and timeliness in industrial wireless sensor networks. *Multimed Tools Appl* 77, 4491–4508 (2018). <https://doi.org/10.1007/s11042-017-4832-5>
- [30] Liu Y, Qin Z, Elkashlan M, Ding Z, Nallanathan A, Hanzo L (2017) Nonorthogonal Multiple Access for 5G and Beyond. *Proceedings of the IEEE* 105(12):2347–2381. <https://doi.org/10.1109/JPROC.2017.2768666>
- [31] M Series (2015) IMT vision—Framework and overall objectives of the future development of IMT for 2020 and beyond. Recommendation ITU-R M.2083-0
- [32] Molisch AF et al (2004) IEEE 802.15. 4a channel model-final report. *IEEE P802 15(4)*: 1–41
- [33] Montalban J et al (2018) Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques. *IEEE Communications Magazine* 56(3): 91-95. <https://doi.org/10.1109/MCOM.2018.1700660>
- [34] Montalban J et al (2020) NOMA-Based 802.11n for Industrial Automation. *IEEE Access* 8:168546-168557. <https://doi.org/10.1109/ACCESS.2020.3023275>
- [35] Montgomery K, Candell R, Liu Y, Hany M (2020) Wireless user requirements for the factory workcell. US Department of Commerce, National Institute of Standards and Technology.
- [36] Nawaratne R, Bandaragoda T, Adikari A, Alahakoon D, De Silva D, Yu X (2017) Incremental knowledge acquisition and self-learning for autonomous video surveillance. *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, IEEE, Beijing, pp. 4790-4795. <https://doi.org/10.1109/IECON.2017.8216826>
- [37] Park SI et al (2016) Low Complexity Layered Division Multiplexing for ATSC 3.0. *IEEE Transactions on Broadcasting* 62(1): 233-243. <https://doi.org/10.1109/TBC.2015.2492459>
- [38] Pedersen K, Pocovi G, Steiner J, Maeder A (2018) Agile 5G scheduler for improved E2E performance and flexibility for different network implementations. *IEEE Communications Magazine* 56(3): 210-217. <https://doi.org/10.1109/MCOM.2017.1700517>
- [39] Rondón R, Gidlund M, Landernäs K (2017) Evaluating bluetooth low energy suitability for time-critical industrial iot applications. *International Journal of Wireless Information Networks* 24(3): 278-290. <https://doi.org/10.1007/s10776-017-0357-0>
- [40] Sachs J, Wikstrom G, Dudda T, Baldemair R, Kittichochechai K (2018) 5G radio network design for ultra-reliable low-latency communication. *IEEE network* 32(2): 24-31. <https://doi.org/10.1109/MNET.2018.1700232>
- [41] Schulz P et al (2017) Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture. *IEEE Communications Magazine* 55(2): 70-78. <https://doi.org/10.1109/MCOM.2017.1600435CM>
- [42] Seijo O, Fernández Z, Val I, López-Fernández JA (2018) SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks. *14th International Workshop on Factory Communication Systems (WFCS)*, IEEE, Imperia, pp. 1-10. <https://doi.org/10.1109/WFCS.2018.8402358>
- [43] Tramarin F, Vitturi S, Luvisotto M, Zanella A (2016) On the Use of IEEE 802.11n for Industrial Communications. *IEEE Transactions on Industrial Informatics* 12(5): 1877-1886. <https://doi.org/10.1109/TII.2015.2504872>
- [44] Varghese A and Tandur D (2014) Wireless requirements and challenges in Industry 4.0. *International Conference on Contemporary Computing and Informatics (IC3I)*, Mysore, pp. 634-638. <https://doi.org/10.1109/IC3I.2014.7019732>

- [45] Zhang L et al (2016) Layered-Division-Multiplexing: Theory and Practice. IEEE Transactions on Broadcasting 62(1):216-232. <https://doi.org/10.1109/TBC.2015.2505408>
- [46] Zhang L et al (2019) Layered-Division-Multiplexing for High Spectrum Efficiency and Service Flexibility in Next Generation ATSC 3.0 Broadcast System. IEEE Wireless Communications 26(2): 116–123. <https://doi.org/10.1109/MWC.2018.1800092>
- [47] Zhang L et al (2020) Using non-orthogonal multiplexing in 5G-MBMS to achieve broadband-broadcast convergence with high spectral efficiency. IEEE Transactions on Broadcasting. <https://doi.org/10.1109/TBC.2020.2983563>

3.2.6 Aldizkari-artikula (A7)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengo da:

- E. Iradier and J. Montalban, "Komunikazioak 4.0 Industrian," Elhuyar Aldizkaria aldizkarian argitaratzeko onartua.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: Elhuyar Aldizkarian indexatutako online aldizkari artikulua
- Saila: Jakintza-alor anitzekoa

Komunikazioak 4.0 Industrian

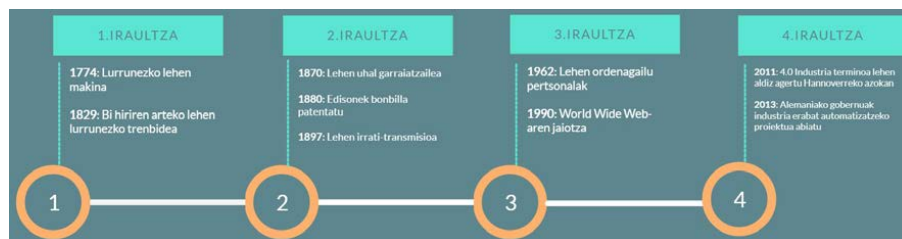
Eneko Iradier, doktoretza aurreko ikertzailea Bilboko Ingeniaritza Eskolan (EHU)

Jon Montalban, irakaslea Gipuzkoako Ingeniaritza Eskolan (EHU)

Azken mendeetan, industria-iraultzek markatu dute garapen teknologikoaren erritmoa. Une honetan, laugarren industria-iraultza (4.0 Industria), garatzen ari da. Bereziki, komunikazio-sistemak dira prozesu honen gidariak. Baina, nola eraldatu beharko dira komunikazio-sistema tradizionalak? Nolako izango da etorkizuneko industria?

Iraganera begira

Egokitzeko eta eboluzionatzeko gaitasuna da gizakia bereizten duen ezaugarrietako bat. Hori dela eta, historian zehar hiru industria-iraultza bizi izan ditugu sektore espezifikoen garapenaren ondorioz. Zehazki, lehenengo industria-iraultza mekanizazioaren garapenak bultzatu zuen; bigarrena, energia elektrikoaren ekoizpen masiboak eta industria kimiko eta automobilistikoaren garapenak eta hirugarrena, mikroelektronika eta informazioaren teknologiak ekoizpen-kateetan sartzeak. Gaur egun, aurrerapen informatiko ugariak, tresna digital berrien garapenak eta, batez ere, makinen eta prozesuen automatizazioak laugarren industria-iraultzaren hasieran jartzen gaitu, hots, 4.0 Industria izenez ezagunagoa den iraultzaren hasieran. Laugarren industria iraultza honen helburua lantegi adimendunen edo 'smart-industry' delakoan garapena da, modu autonomo eta adimentsuan planifikatu, aurreikusi, kontrolatu eta ekoizteko gaitasuna izango lukeena, eta hortaz, funtzionamendu eta ekoizpen-kateari balio handiagoa emango liokeena.



1. Industria-iraultzen denbora-lerroa

Zer da 4.0 Industria?

Komunikazioak 4.0 Industriaren funtsezko ezaugarria izango dira. Izan ere, fabrika adimendunak ahalbidetzeko, industria osatzen duten makina bakoitzari elkarren artean komunikatzeko eta elkarrekin konektatuta egoteko gaitasuna eman beharko zaio. Hala ere, horrelako komunikazioak ezartzea zailtzen duten zenbait oztopo daude.

Lehenik eta behin, komunikazio kableatuetatik haririk gabeko komunikazioetarako trantsizioak oraindik ez ditu beharrezko bermeak eskaintzen. Tradizionalki, industria-komunikazioak sistema kableatuetan oinarritu izan dira; alabaina, horrelako komunikazioak ez dira egokiak sareen tamaina handitzeko edo ekipoei mugikortasuna emateko. Horregatik, haririk gabeko teknologiak dira hautagai egokiak, nahiz eta oraindik sistema kableatuen sendotasuna ezin duten bermatu.

elhuyar

zientzia eta teknologia

Bestalde, aplikazio-ingurunea beste erronka bat da, berez. Aplikazio-lekuak (lantegiak, ekoizpen-plantak, e.a.) ingurune itxiak izan ohi dira, ekipoen kontzentrazio handiarekin eta islapenak sortzen dituzten ekipo metaliko askorekin. Faktoreen konbinazio horren ondorioz, jasotako seinalea oihartzun ugari osatuta dago eta hedapen-kanal bortitz batez eraginda. Zalantzarik gabe, harrera baldintza horiek komunikazioak zailtzen dituzte, eta erronka bat planteatzen dute: ingurune horietarako egokiak diren sistema ultra-sendoak diseinatzea.

Azkenik, haririk gabeko komunikazioetan erabiltzen diren frekuentzia-bandak beste erronka nagusietako bat dira. Haririk gabeko sistema gehienek, ISM (Industrial, Scientific and Medical) banda libreak erabiltzen dituzte. Banda horiek konkurrentzia handia dute, eta, beraz, sareak kongestionatu egin daitezke, paketeen arteko talkara iritsiz edo ekipo jakin batzuetarako sarbidea galaraziz.

Gaur egungo eskaintza teknologikoa

Lehenengo eta behin, momentuz industria-komunikazioak unibertsaliki definitzen dituen estandar edo teknologiarik ez dagoela aipatu beharra dago. Horregatik, amaierako aplikazioaren edo ingurunearen arabera, hainbat aukera teknologiko daude.

WiFi-a oso onartuta dagoen irtenbidea da. Zalantzarik gabe, teknologia hori bultzatzeko argudio nagusia gaur egungo hedapena da; izan ere, egungo enpresa guztiek edo ia guztiek kudeatzen baitute beren WiFi sare propioa. Hori dela eta, ekipo automatizatuak sare horretan sartzeak kostu txikiagoa dakar sare berri eskusibo baten hedapenarekin alderatuta. Alabaina, teknologia honek ere baditu bere desabantailak, ez baitu komunikazioen fidagarritasuna bermatzen duen mekanismorik inplementatzen, ezta determinismorik ere. Horregatik, ikerketa asko bideratu dira bi puntu ahul horiek sendotzera, ingurunerako sarbidea modu ordenatuan koordinatzen duten eta komunikazioen sendotasuna hobetzeko mekanismoak ezartzen dituzten denbor-eskemak garatuz, besteak beste, paketeen berbidalketa edo erredundantzia.

Hautagaien rankingaren goiko postuetan Bluetooth-a aurki daiteke, bereziki, Bluetooth Low Energy (BLE) soluzioa. BLE ekipoen interkonexiora bideratutako teknologia da, non nodoak maisu-rola betetzen duten ekipoekin konektatzen diren. Irtenbide horren sendotasuna energia-kontsumo baxuan datza, eta horrek eragiten du, hain zuzen, oso teknologia interesgarria izatea batera duten ekipoen aplikazioetarako, hala nola, sentsore-sareetarako. WiFi-arekin alderatuta, ordea, BLE-k datu-tasa txikiagoa du (2 Mbps) eta horrek informazio gutxi transferitzea eskatzen duten aplikazioetara mugatzen du.

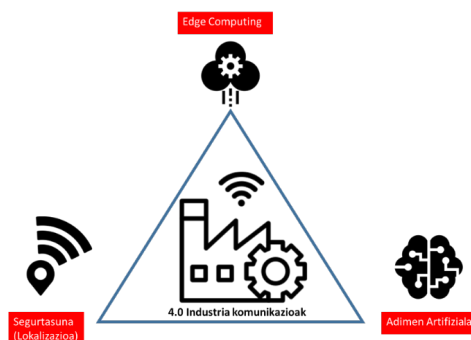
Bukatzeko, banda zabaleko komunikazio-sistema mugikorrek ere proposatu dira zenbait behar asetzeko. Horien artean, aipatzekoa da komunikazio mugikorren laugarren belaunaldiaren erabilera, Long Term Evolution (LTE), esaterako, Internet of Things-era (IoT) bideratutako sare eta aplikazioei euskarria emateko erabili izan dena. Irtenbide horri Narrow Band IoT deritzo eta, BLE bezala, datu tasa txikien transmisioan oinarritzen da erabiltzaile kopuru handi bati zerbitzua emateko.

Une honetan, ikerketa 5G aldera bideratzen ari da, komunikazio mugikorren bosgarren belaunaldiak industria-betekizunen antzeko modalitate bat baitu. Hala ere, oraindik garapen-fasean dagoenez, ez dago arrakastaren bermea ematen duen lan esperimentalik.

Etorkizunari begira

Gaur egun, irratikomunikazioen mundua geldiezinezko abiaduran doa aurrera, batez ere, telefonia mugikorraren bultzadari esker. Izan ere, orain dela gutxi hedabideetara heldu den 5G teknologiaren hedapenaren hastapenean gauden honetan, ikerkuntzaren munduan 6G ezizenaz ezagutzen den hurrengo fasearen gaineko lanak gero eta nabariagoak dira. Etengabeko bilakaera honen erritmoa ezin da esparru guztietara hedatu eta 4.0 Industriaren aplikazioek, esaterako, beren ibilera propioa markatu behar dute. Horrenbestez, aurretik aipatu den bezala gaur egun 5Gren barruan jada onartuak eta lege diren hainbat teknologia oraindik probatzeke daude industria-komunikazioen alorrean.

Aipatzekoak dira seinalearen atzerapena (edo prozesaketa denbora) murrizten duten teknikak. Hauen artean, nabarmentzekoak da *Edge Computing* esparru honetan inportantea izan daitekeen aldatetaren eredu gisa. Laburki, honen helburua sarearen lanak muturrera eramatean datza, hots, datuak sortu diren iturritik gertu; modu horretan, muturretik muturrera informazioa garraiatzeko beharrezkoa den denbora gutxituz. Bestetik, beste alor batzuetan oso ezaguna den *Cloud Computing*-ak ere garrantzia izan lezake industria-komunikazioetan, baina horretarako honi lotutako atzerapen denborak murriztu beharko ziratekeen.



2. 4.0 Industriaren etorkizuneko ardatzak

Arestian aipatutako, eta komunikazio mugikorretatik oinordetzan hartutako irtenbideez gain, haririk gabeko industria-komunikazioetarako aipagarriak izan daitezkeen teknologia handizaleagoak ere badira. Azken urtean, Nature aldizkariaren arabera, *Adimen Artifiziala (AA)* laugarren postura igo da gehien bilatutako ikerkuntza terminoen artean. Ez da harritzekoa, beraz, laugarren industria iraultza honetan ere hainbat alorretan eragina aurreikustea: energia sorkuntza eta banaketa sistemetan, IoT eta sentsore sistemetan, kontrolaren monitorizazioan e.a. Zerrenda horretan haririk gabeko irratikomunikazioak ere koka daitezke. AA oso erabilgarria izan daiteke lantegi berrien komunikazio sareen plangintzarako. Orain arte, plangintza tradizionalen transmisoreak estatikotzat jotzen ziren, hartzaileak baitziren mugikortasuna zuten gailu bakarrak. Alabaina, lantegi-adimendu batean konektatuta egon daitezkeen gailu kopurua eta tipologia handitzen doa etengabe, igorleak barne eta horrenbestez, etorkizuneko lantegi baten estaldurarako planifikazio estatikoak muga nabariak ditu. Bestalde, AAk ere ekarpena egin dezake eraso baten aurrean haririk gabeko komunikazioek daukaten babes eskasaren aurrean. Adibidez, AA teknikak erabiliz sareko trafikoa azter daiteke, eta, aurretiaz ondo entrenatutako eredu bidez, gure sarean gerta daitezkeen eraso maleziatsuak identifika daitezke trafikoan aldaera susmagarriak aztertuz.

elhuyar

zientzia eta teknologia

Bestetik, 4.0 Industriaren alorrean irrtati-komunikazioak segurtasun fisikoaren ardatz berri gisa ere uler daitezke. Azken urteetan argitaratutako ikerketek erakutsi dute haririk gabeko sistemek informazioa garraiatzeaz aparte, beste hainbat xede ere bete ditzaketela, esaterako, gela baten barruan dauden pertsonak zenbatzeko edota pertsona horiek egiten ari diren jardura zehazteko. Hitz gutxitan, hori lortzeko pertsonen presentziak igorritako seinalean eta zeharkatutako kanalean izandako aldaketak estatistikoki aztertu behar dira. GPS teknologia erabili ezin den esparru batean, irtenbide hobeezina izan daiteke edozein arrisku edo istripuren aurrean langileak lokalizatuta eta zenbatuta izateko. Zalantzarik gabe, horrelako identifikazio sistemak inplementatzea, eta hauek aurretiaz azaldu diren AA teknikoekin bateratzea, ezinbesteko ikerkuntza lerroa da etorkizuneko lantegi adimentsuen garapen seguruentzako.

Azken gogoetak

4.0 Industria iritsi da jada eta haririk gabeko komunikazioen eraldaketa sakona eskatzen du. Egungo eskaintza teknologikoak hainbat hautagai aurkezten ditu, baina batek ere ez ditu jarraitu beharreko ereduak izateko ezaugarri guztiak betetzen. Horregatik, ikerketa- eta garapen-prozesuak jarraitu egin behar du, eta dagoeneko dauden teknologiak errendimendua hobetuko duten teknika disruptiboekin konbinatu beharko dira etorkizuna oraindira ekartzeko.

Bibliografia

R. Drath and A. Horch, "Industrie 4.0: Hit or Hype? [Industry Forum]," in IEEE Industrial Electronics Magazine, vol. 8, no. 2, pp. 56-58, June 2014.

A. Varghese and D. Tandur, "Wireless requirements and challenges in Industry 4.0," 2014 International Conference on Contemporary Computing and Informatics (IC3I), Mysore, 2014, pp. 634-638.

K. Montgomery, R. Candell, Y. Liu, and M. Hany, "Wireless user requirements for the factory workcell," NIST Report, Adv. Manuf. Ser.(NISTAMS)-300, vol. 8, 2019.

3.3 3. ekarpenarekin erlazionatutako artikuluak

3.3.1 Konferentzia-artikula (K5)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- L. Zhang, Y. Wu, Wei Li, S-I. Park, J-Y. Lee, H-M. Kim, N. Hur, E. Iradier, P. Angueira and J. Montalban, "ATSC 3.0 In-band Backhaul for SFN Using LDM with Full Backward Compatibility," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Korea (South), 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.8971918.

Hona hemen artikulu honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore-n indexatutako konferentzia
- Saila: Konputazio zientziak eta ingeniari-tza
- SJR faktorea: 0,300

ATSC 3.0 In-band Backhaul for SFN Using LDM with Full Backward Compatibility

Liang Zhang, Yiyang Wu, Wei Li
Communications Research Centre,
Canada

Sung-Ik Park, Jae-young Lee,
Heug-Mook Kim, Namho Hur
Electronics and Telecommunications
Research Institute, Korea

Eneko Iradier, Pablo Angueira
and Jon Montalban
University of Basque Country, Spain

Abstract— In BMSB’2018, the authors presented a paper on using Layered-Division-Multiplexing (LDM) to deliver in-band backhaul of robust mobile services for ATSC 3.0 Single-Frequency-Netowrk (SFN) transmitters and gap-fillers [1]. Only robust mobile services are backhauled to form an SFN in indoor or isolated environments to extend and improve reception Quality of Experience (QoE) for mobile devices. This paper proposes a complete in-band backhaul approach that provides backhaul for both robust mobile and high-data-rate fixed services. The proposed solution uses LDM to carry backhaul data alongside broadcast data intended for reception by the public. The system is fully backward compatible with the ATSC 3.0 Next Gen TV service, causing no degradation on consumer service reception. The scheme can greatly reduce broadcasters’ operating costs, while improving service quality – especially for mobile, handheld and indoor reception. In comparison to On-Channel-Repeater (OCR), the proposed system can provide SFN service with flexible emission timing control. The regenerated signals at each transmitter can have high SNR to meet RF spectrum mask requirement and support multi-hop operation. A multi-hop backhaul system can form a mesh network for reliability (re-route in case of one transmitter failure), and scalability to follow the population and market growth. The proposed system can deliver backhaul not only for SFN broadcast services, but also for non-broadcast data distribution, such as IoT and connected cars.

Keywords— LDM, SFN, STL, In-band Backhaul, Mesh Network, Full-Duplex Transmission,

I. INTRODUCTION

With the rapidly increasing number of mobile and handheld devices, delivering robust mobile services becomes a necessary capability for the next generation TV broadcasting system, also known as ATSC 3.0 [2]. Many earlier studies have shown, however, that it is quite challenging to provide good mobile service coverage using the existing high-tower-high-power (HTHP) single transmitter approach. Single Frequency Networks (SFN) with multiple transmitters is a preferred infrastructure that can significantly improve quality of experience (QoE), especially for small-size handheld and portable receivers in challenging environments, such as indoor locations. Implementing SFN requires deploying multiple low-

power SFN transmitters (SFN-Txs) in addition to the existing HTHP facilities.

An example of the current approach to implement an ATSC 3.0 SFN is illustrated in Figure 1. In this example SFN, mixed mobile and fixed services are delivered using Layered Division Multiplexing (LDM) technology [3].

As shown in Figure 1, deploying each additional SFN-Tx requires a distribution link, or backhaul, also called a Studio-to-Transmitter Link (STL), to deliver the service data and control signaling from a Broadcast Gateway (BGW). In current systems, STLs are implemented using either fiber circuits or dedicated microwave links. Fiber links are not always available at desired locations and are expensive to install or to rent. Microwave spectrum often is scarce, and installation is also very costly. Consequently, a new solution is required for SFN distribution links that offers both low installation and low operation costs.

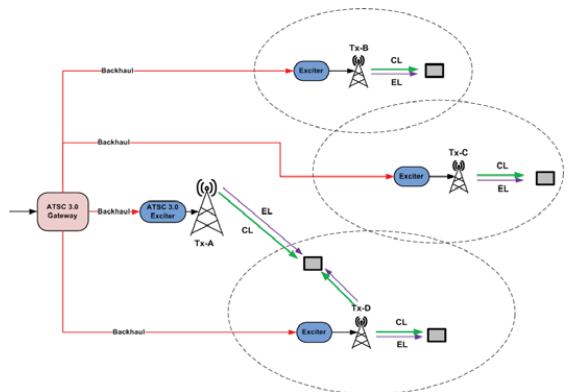


Figure 1: A 2-Layer ATSC 3.0 Single Frequency Network

II. BACKWARD-COMPATIBLE WIRELESS IN-BAND BACKHAUL USING LDM

The use of wireless in-band backhaul distribution links is a promising alternative solution, offering both low infrastructure and operational costs, and high spectrum efficiency for ATSC 3.0 SFN deployments.

This work was supported by Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.2017-0-00081, Development of Transmission Technology for Ultra High Quality UHD). This work has been partially supported by the Basque Government under the PREDOC grant program (PRE_2018_1_0344), and Project 61420106008.

During transition period, ATSC 1.0 and ATSC 3.0 programs must co-exist. Since there is no new spectrum allocated for transition, broadcasters need to collaborate so that more than one ATSC 3.0 programs be transmitted in one 6MHz RF channel. Meanwhile, ATSC 3.0 with HEVC and LDM technologies can accommodate many programs in a 6 MHz channel. For example, LDM Core Layer (CL) with data rate of 4 Mbps can deliver 2 x 720p, or 6 x 480p programs for robust mobile service, while Enhanced Layer (EL) with data rate of 18 Mbps can provide 4 x 1080p, or 8 x 720p programs for fixed service. Statistical multiplexing can further increase the number of programs by 20-30%. Scalable video coding can also reduce the video data rate, or improve the video quality. Therefore, using part of the ATSC 3.0 data capacity for in-band backhaul is viable.

Figure 2 shows the basic concept of using wireless in-band backhaul in an ATSC 3.0 SFN. The main transmitter, Tx-A, is an existing high-power transmitter that has a dedicated STL connection to the BGW. Tx-A receives the STL data for each new secondary SFN-Tx (Tx-B/C/D) and modulates it onto part of the ATSC 3.0 signal for over-the-air transmission. This yields an in-band solution because the backhaul data distribution shares the same spectrum as the broadcast services.

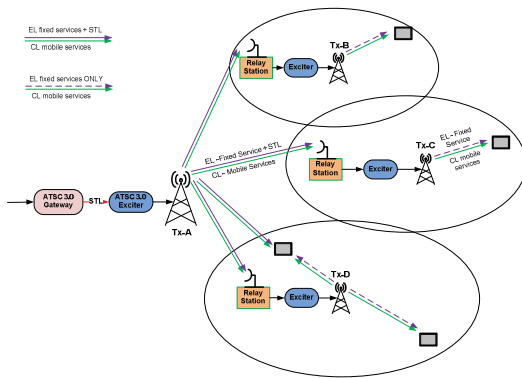


Figure 2: Using LDM to implement in-band wireless backhaul

To achieve higher combined backhaul and broadcast-service throughput, LDM is used to combine backhaul data and broadcast-service data within one RF TV channel. In this case, the main transmitter, Tx-A, transmits a 2-layer LDM signal wherein CL delivers robust mobile services and part of EL capacity delivers backhaul data for the secondary SFN-Tx's. At each secondary SFN-Tx, an SFN relay receiver (RL-Rx) is implemented to decode the backhaul data from the received LDM signal. The decoded data is then fed to an ATSC 3.0 Exciter to generate the SFN broadcast-service signal for emission.

III. SFN AND BACKHAUL DATA TIMING AND SYNCHRONIZATION

To achieve SFN operation, the re-transmitted signals from the secondary SFN-Tx's (Tx-B/C/D) need to be frequency- and time-synchronized with the signal emitted from the main transmitter, Tx-A. Such synchronization requires the backhaul data from Tx-A to have a time advance relative to the broadcast service signal. This time-advance needs to be sufficiently long to allow the RL-Rx's to decode the backhaul data and the related transmitters to re-encode/re-modulate it into the SFN broadcast-service signal. Consequently, a timing control mechanism is required. For example, if T is the required time advance and $X(t)$ is the broadcast service data, backhaul data should be transmitted as $X(t-T)$. In case of multiple-hop backhaul with n -hop, the backhaul data from different RL-Tx should be $X(t-nT)$, $X(t-nT+T)$, $X(t-nT+2T)$, ... $X(t-T)$, respectively.

When using part of the EL signal for backhaul data distribution, the fixed broadcast service (FBS) delivery capacity of the EL is reduced. This EL capacity loss can be mitigated by installing high-gain antennas at high elevation for the RL-Rx's, which provides high reception signal-to-noise ratio (SNR) and a stationary close to line-of-sight (LOS) channel for backhaul signals. These conditions allow the use of high-order modulation (e.g., 1024QAM or 4096QAM) and high channel coding rate, thereby reducing the percentage of transmission capacity required for backhaul transmission.

IV. MULTIPLE SCENARIOS OF IN-BAND BACKHAUL SOLUTIONS USING LDM

There are different implementation scenarios for LDM in-band backhaul, which are shown in Figure 3. Figure 3(a) and 3(b) present scenarios with 2-layer LDM, which are fully backward compatible with the current ATSC 3.0 standard. There is no performance impact to consumer receivers. In Figure 3(a), the backhaul data of both mobile and fixed services are distributed/backhauled in EL. There is no capacity loss in CL for robust mobile services. In Figure 3(b), a dedicated single-layer portion is allocated for backhaul data delivery for both CL mobile and EL fixed services, which is essentially a time-division-multiplexing (TDM) approach for in-band backhaul signal transmission. While this approach allocates more transmission power to backhaul signal and removes the need for CL cancellation at the RL-Rx, it suffers capacity loss in both the CL and EL signals.

A third LDM signal layer can be added to the current 2-layer ATSC 3.0 signal to deliver the backhaul data of the CL mobile services. Figure 3(c) and Figure 3(d) shows two possible signal configurations. In this solution, the third signal layer has very low power and is configured with strong coding and modulation that is similar to those of the CL mobile services. In order to decode the backhaul data in the third signal layer and limit its impact to the EL fixed services, the SFN Relay Station (SFN-RS) needs very high SNR. Therefore, it is necessary for the SFN-RS to have high dynamic range tuner and directional antenna at high elevation. Adding the third layer could reduce the broadcast service capacity loss.

The power of this third layer needs to be carefully designed to have negligible impact on the broadcast service data reception.

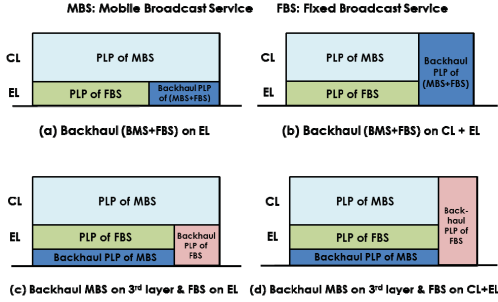


Figure 3: LDM signal structure for wireless In-band backhaul

In both scenarios shown in Figure 3(c) and (d), the EL backhaul data are transmitted using separate PLPs, in order to reduce the spectrum consumption and, therefore, the impact to fixed 4k-UHD service delivered in EL. In addition, the CL backhaul signal in the third layer does not overlap with the EL backhaul signal. This helps to increase the EL backhaul signal SNR (without the third layer as interference), and allow it to use higher order modulation and coding parameters.

Since backhaul links generally have stationary near-LOS channel and operate at high SNR conditions, high order modulation and high coding rate could be used, which results in less than 1/3 of the RF channel capacity required for backhaul data for all the broadcast services, i.e., both CL mobile and EL fixed services. When MIMO and other advanced technologies are used for backhaul transmission, the total channel capacity loss can be reduced to 10% to 12%.

V. IN-BAND BACKHAUL SIGNAL DETECTION AT RELAY STATIONS

A. Backhaul Signal Detection

A simple block diagram of an SFN-Tx is shown in Figure 4, where a high-gain directional antenna is installed at the RS-Rx pointing to the main transmitter, Tx-A. This antenna provides high SNR and near LOS channel condition for backhaul signal contained in the 2-layer LDM signal emitted by Tx-A, which is referred to as forward signal (FWS).

Figure 4 also shows a major challenge for full-duplex in-band backhaul system, also known as self-interference. The RS-Rx antenna not only receives the FWS from Tx-A, but also the re-transmission signal from the SFN-Tx transmitter (Tx-B) antenna, which is referred to as loopback signal (LBS).

Assuming a 2-layer LDM transmission with in-band backhaul structure as shown in Figure 3B, the signal models of the FWS and LBS are plotted in Figure 5. In the FWS, 2-layer LDM is deployed to deliver mobile broadcast services (MBS) in CL and fixed broadcast services (FBS) in EL. A dedicated

single-layer time-slot is assigned to deliver STL data of both MBS and FBS.

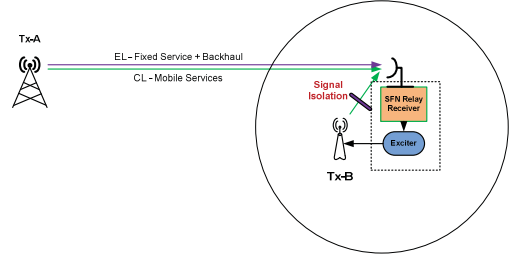


Figure 4: Backhaul signal detection at RS-Rx

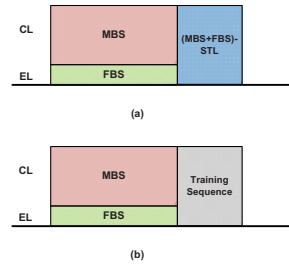


Figure 5: Signal model at SFN-Tx relay receivers;
(a) Received signal from Tx-A with backhaul data;
(b) Transmission signal of RS-Rx

For broadcast services, a careful timing adjustment is required so that the FWS and LBS deliver time and frequency-synchronized SFN services. On the other hand, as shown in Figure 5, the re-transmission signal from Tx-B during the backhaul time slot becomes an interference for backhaul data detection.

The received signal OFDM symbols in the k th subchannel at the RS-Rx during the backhaul time slot can be expressed as,

$$Y_{RL}(k) = X_{BH}(k) \cdot H_{FW}(k) + \sqrt{\kappa_{LB}} \cdot X_{LB}(k) \cdot H_{LB}(k) + N_0(k) \quad (1)$$

where X_{BH} is the backhaul signal transmitted from Tx-A; X_{LB} is the transmission symbols from Tx-B (the relay transmitter); H_{FW} is the normalized forward channel response from Tx-A to RS-Rx; H_{LB} is the normalized loopback channel response, κ_{LB} is the power ratio of the LB signal over the FW signal, and N_0 is the thermal noise power.

Ideally, if Tx-B has the option of transmitting a "Null" signal with zero-power, i.e., $X_{LB}(k) = 0$, there would be no self-interference. This, however, is not possible in ATSC 3.0. Even when Tx-B does not use this part of time allocation for service/backhaul data transmission, it needs to fill dummy

symbols in order to ensure a constant transmission power. These dummy symbols are known to the RS-Rx receiver and can be used as a training sequence for loopback channel estimation and self-interference cancellation.

Since the transmitter antenna and the RS-Rx receiver antenna are closely located at the SFN-Tx, the loopback signal power could be significantly higher than the forward signal. This could impact the reception performance of the backhaul signal. This is the same case as full duplex transmission, where data are transmitted-received in both directions on the same spectrum at the same time [4].

To reduce the impact of the loopback signal, a signal isolation (SI) module could be implemented at the SFN-Tx, which attenuates the received loopback signal power at the RS-Rx, as shown in Figure 4. Good isolation between the SFN Tx antenna and the backhaul receiving antenna can be achieved by using antenna distance, blocking, antenna directivity and polarization, and other isolation schemes. Tests showed that 70-80 dB isolation can be achieved in practical conditions.

However, for medium-power SFN re-transmitter, even with a good SI, the loopback signal power could still be ten to hundred times (10-20 dB) higher than that of the forward signal. Loop back signal cancellation needs to be applied,

$$\begin{aligned} Y_{BH}(k) &= X_{BH}(k) \cdot H_{FW}(k) \\ &= Y_{RL}(k) - \sqrt{\kappa_{LB}} \cdot X_{LB}(k) \cdot \hat{H}_{LB}(k) \end{aligned} \quad (2)$$

where \hat{H}_{LB} is the loopback channel estimate.

The signal to noise ratio (SNR) of the backhaul signal after the loopback signal cancellation can be calculated as,

$$\gamma_{BH}(k) = \frac{1}{\kappa_{LB} \cdot v_H^2 + N_0} \quad (3)$$

where v_H^2 is the mean square error (MSE) of the loopback channel estimate. Therefore, the key technology for good loopback signal cancellation is the channel estimation module.

Since the backhaul signal takes away part of the transmission resource for service delivery, it is desirable that the backhaul signal be configured using high modulation order and high coding rate. This configuration, however, requires high SNR for signal detection. From Eq-3, a high SNR for backhaul signal requires low residual loopback signal power after the loopback cancellation. This translates into low channel estimation MSE, especially for high loopback signal power.

The loopback channel could be estimated using decision-directed channel estimation algorithms, since the loopback signal is known to the RS-Rx. The Least Square (LS) channel estimates in each subchannel is first obtained as,

$$\tilde{H}_{LB}(k) = \frac{Y_{RL}(k)}{X_{LB}(k)} = H_{LB}(k) + \frac{Y_{FW}(k) + N_0(k)}{X_{LB}(k)} \quad (4)$$

where the received forward signal from Tx-A, $Y_{FW}(k)$, is treated as an additional noise.

Both frequency-domain and time-domain filtering can be applied to the LBS estimate to enhance the channel estimation accuracy.

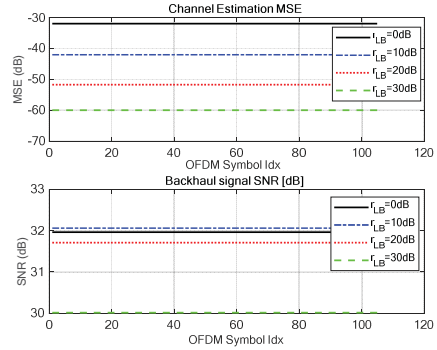


Figure 6: Loopback signal cancellation performance

B. Loopback Signal Cancellation Simulation Results

Matlab simulations are conducted to evaluate the performance of loopback signal cancellation with a practical two-dimensional channel estimator (2D-CE), where Wiener filtering is applied in both frequency-domain and time-domain.

Due to the short distance between the RS-Rx receive antenna and the SFN transmitter antenna, the loopback channel should be characterized as either a near-LOS channel or a multipath channel with short delay spread. In simulations, a shortened multipath channel is used following the characteristics of Typical Urban (TU) channel [5], where the mean delay spread is defined as 0.1 μsec , and the maximum delay spread is 0.7 μsec .

In simulations, an ATSC 3.0 system is assumed with transmission mode of 16k FFT. The forward signal has an SNR of 25 dB. For good understanding of the impact from the loopback signal power, four loopback over forward signal power ratios are considered: [0 10 20 30] dB.

Figure 6 summarizes the simulation results of the loopback signal cancellation. In the upper subplot, the average powers of the residual loopback signal after cancellation are plotted; the lower subplot shows the SNR of the backhaul signal taking into account of only the residual loopback signal power.

For higher loopback signal power, the channel estimate is more accurate, due to the lower interference level from the forward signal, $Y_{FW}(k)$, in Eq-2. For loopback signal power of [0 10 20 30] dB, the 2D-Wiener channel estimator can achieve MSE of [-30 -41 -51 -60] dB.

For all tested scenarios, after cancellation, the residual loopback signals are all 30+ dB lower than the backhaul signal received from the main transmitter. For backhaul signal with an SNR threshold of 25 dB, this residual loopback signal introduces very minor impact on the backhaul data detection.

It needs to be pointed out that the loopback signal only impacts the backhaul signal reception. It has absolutely no impact on the broadcast service reception by the ATSC 3.0 consumer receivers. The backhaul signals are simply ignored by the consumer receivers.

VI. MULTI-HOP IN-BAND BACKHAUL AND MESH NETWORK

Because each backhaul relay station regenerates the broadcast service signal, multi-hop backhaul is viable. Figure 7(a) demonstrates a 3-hop STL mesh network. The network is scalable that more Tx's can be added to extend or shape the coverage to meet the market growth. If one SFN transmitter fails, the backhaul network can be re-routed to recover the service, Figure 7(b). The coverage radiuses in Figures 4 indicate fixed EL service. The robust CL service should fully recover the failed Tx service area.

VII. ON-CHANNEL REPEATERS VS. IN-BAND BACKHAUL

A. On-Channel Repeater

On-channel repeater (OCR) has been available for many years as a low-cost solution to extend broadcast service coverage areas and to fill coverage holes [6]-[9]. An OCR basically receives the broadcast signal from a main transmitter (MTx), amplifies the signal, and re-transmits on the same RF channel. An OCR output signal SNR is always lower than the input signal SNR. It is difficult to implement a multi-hop OCR system, while still meets the RF spectrum mask requirement. The emission time of the OCR cannot be adjusted.

The main issue with OCR is the feedback signal from the re-transmission antenna to the receiving antenna, which can have significantly higher feedback power than the received signal from the MTx. This feedback signal can cause system oscillations and instability that disable the effective operation of the OCR [8].

Isolation mechanism becomes the critical component for OCR to reduce the feedback signal power. Most existing OCR solutions use both physical isolation and echo cancellation (EC) to achieve sufficient isolation performance. Physical isolation by antenna placement and antenna pattern design can usually reduce the loopback signal power by 30 to 50 dB, which might not be sufficient. The additional isolations are usually achieved by EC, where decision-feedback EC based EC (DF-EC) and FIR-filter-based EC (FIR-EC) are the two most popular solutions.

The DF-EC is able to provide up to 30 dB feedback signal cancellation for a single carrier modulation system, such as ATSC 1.0 [9]. It is, however, not applicable to the ATSC 3.0 system that uses OFDM modulation. For SFN, the emitted signal from OCR should fall within the equalization range of consumer receivers. In the case of OFDM systems, all signals from different transmitters must fall within the Cyclic Prefix (CP), or Guard Interval (GI). Using DF-EC requires the demodulation of the frequency-domain signal symbols, and therefore a delay of at least one FFT duration, without even counting the delays for time interleaving and re-modulation. The GI in ATSC 3.0 is at most $\frac{1}{4}$ of FFT duration. Hence, OCR output signal will be emitted outside the GI of the signal

from the main transmitter. This will result in significant co-channel interference.

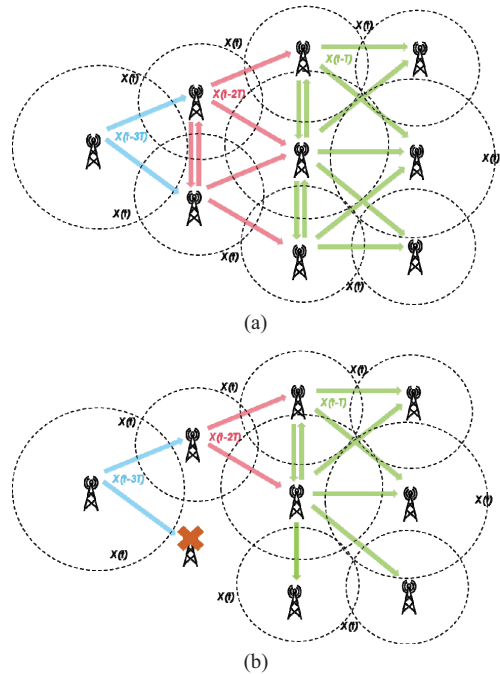


Figure 7: Multi-hop in-band backhaul SFN network:

(a) SFN Mesh Network;

(b) SFN mesh network with Tx failure and re-route.

The FIR-EC solutions could be implemented to achieve low delay. However, since linear equalization causes noise enhancement, received signal at OCR from the main transmitter must have very high SNR, or the received signal strength must be very high.

In summary, OCR has certain operating restrictions:

- OCR requires a good quality input signal with very high SNR and low multipath distortion to operate. The OCR signal output SNR is always worse than the input SNR.
- While existing EC techniques could achieve good cancellation performance, their stable operation and effectiveness are not guaranteed, due to the dynamic multipath characteristics of the feedback channel conditions. For challenging scenarios, existing OCR solutions could end-up in oscillation or instable conditions.
- OCR re-transmission power might be limited, and signal emission time cannot be controlled.

- It would be difficult to cascade the OCR operation due to signal SNR limitations.
- OCR only retransmits the received signal, no local data insertion of non-broadcast service data, such as IoT and connected car services are allowed.

Therefore, OCR is best used for isolated or enclosed areas.

B. *In-band backhaul*

For In-band backhaul based SFN, the SFN-RS receives the time-advanced backhaul data with equalization/demod/decode to remove all distortions (noise and interference). The regenerated signal is re-encoded and re-modulated to generate a clean/flat SFN re-transmission signal/spectrum. There is a total isolation between re-transmitted and the received signals. The emission timing can be controlled to be within the OFDM system GI range for SFN operation.

The backhaul and loopback signal isolation is also much relaxed. The loopback signal power can be much higher than that of the received signal, the system is still operational. Signal cancellation technology, similar to the one used in the LDM system, can reliably retrieve the backhaul data. Therefore, SFN can transmit a re-generated clean signal that fully complies with the RF spectrum mask regulation, at much higher power level than that of the OCR.

In-band Backhaul Link (IBL) SFN Relay Station behavior:

- IBL is designed for general SFN deployment with full SFN Tx timing control.
- The SFN-RS output SNR is always better than that of the input SNR, due to signal re-generation.
- While IBL SFN-RS requires a good quality input signal to retrieve backhaul data, its requirement is less demanding in comparison to the OCR, which is based on the non-error-corrected feedbacks causing noise enhancement and possible error propagation.
- It is possible to cascade the IBL operation or forming a multi-hop mesh network.
- Backhaul can also carry non-broadcast service data, such as IoT, connected car.
- It is viable to combine the IBL SFN with OCR as the last hop. IBL and OCR can co-exist and complement each other.

In addition, a fundamental advantage of IBL over OCR is that IBL is not necessarily limited to SFN backhaul only. IBL can be used for distributing general-purpose non-broadcast IP-data services, such as IoT, connected car, etc. The only negative impact of IBL the consumption of a small portion of the in-band broadcast data capacity

VIII. CONCLUSIONS

A wireless in-band backhaul system for ATSC 3.0 SFN operation was presented. The system uses LDM transmission to carry backhaul data alongside broadcast service data. The system is fully compatible with the ATSC 3.0 Next Gen TV service, causing no degradation of consumer reception. It can

reduce broadcasters' operating costs, while improving service. It is designed for general SFN deployment with full SFN timing control. Due to signal re-generation, each SFN Tx has high SNR output that multi-hop mesh network can be constructed, which has high service reliability and scalable to the market growth. Backhaul can also carry non-broadcast service data, such as IoT, connected car. The only negative impact of in-band backhaul is the consumption of a small portion of the in-band broadcast data capacity. With the application of MIMO and other advanced signal processing technologies, the percentage of broadcast data capacity reduction could be limited to 10 – 15%.

REFERENCES

- [1] L. Zhang, Y. Wu, W. Li, K. Salehian, S. Laflèche, Z. Hong, S.-I. Park, J.-Y. Lee, H. M. Kim, N. Hur, M. Simon and D. G.-Barquero, "Using Layered-Division-Multiplexing for In-Band Backhaul for ATSC 3.0 SFN and Gapfillers," Proceedings of IEEE Int'l Symposium on Broadband Multimedia Systems and Broadcasting 2018 (BMSB2018), June 6-8, 2018, Valencia, Spain.
- [2] L. Fay, L. Michael, D. Gomez-Barquero, N. Ammar and M.W. Caldwell, "An overview of the ATSC 3.0 Physical Layer Specification," IEEE Trans. Broadcasting, vol. 62, no. 1, part II, pp.154-158, Mar. 2016.
- [3] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H.-M. Kim, J.-Y. Lee, P. Angueira, and J. Montalban, "Layered division multiplexing: theory and practice," IEEE Trans. on Broadcasting, vol. 62, no. 1, part II, pp. 216–232, Mar. 2016.
- [4] D. Kim, H. Li, and D. Hong, "A Survey of In-Band Full-Duplex Transmission: From the Perspective of PHY and MAC Layers," IEEE Communications Survey & Tutorial, vol. 17, no.4, 4th Quarter, 2015.
- [5] COST 207 Report, Digital land mobile Radio Communications, Commission of European Communities, Directorate General, Telecommunications, Information Industries and Innovation, Luxembourg, 1989.
- [6] L. Zhang, et. al., "Wireless In-band Distribution Link using LDM for SFN Transmitters and Gapfillers in ATSC 3.0," Proceedings of IEEE BTS Annual Broadcast Symposium," Washington DC, USA, Oct. 9-11, 2018.
- [7] M. M. Wang, "Dynamic Gain Management for On-Channel Repeaters," IEEE Trans. Broadcasting, vol. 59, no. 4, pp. 685-692, Dec. 2013.
- [8] K. M. Nasr, J. P. Cosmas, M. Bard, and J. Gledhill, "Performance of an Echo Canceller and Channel Estimator for On-Channel Repeaters in DVB-T/H Networks," IEEE Trans. Broadcasting, vol. 53, no. 3, pp. 609-618, Sept. 2007.
- [9] S. W. Kim, Y. T. Lee, S. I. Park, H. M. Eum, J. H. Seo, and H. M. Kim, "Equalization Digital On-Channel Repeater in the Single Frequency Network," IEEE Trans. Broadcasting, vol. 52, no. 2, pp. 137-146, June 2006.

3.3.2 Aldizkari-artikulua (A8)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- L. Zhang, W. Li, Y. Wu, S. Lafleche, Z. Hong, S-I. Park, J-Y. Lee, H-M. Kim, N. Hur, E. Iradier, P. Angueira and J. Montalban, "Using Layered Division Multiplexing for Wireless In-Band Distribution Links in Next Generation Broadcast Systems," in IEEE Transactions on Broadcasting, vol. 67, no. 1, pp. 68-82, March 2021, doi: 10.1109/TBC.2020.2989638.

Hona hemen artikulua honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 69/266 (Q2) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,419

Using Layered Division Multiplexing for Wireless In-Band Distribution Links in Next Generation Broadcast Systems

Liang Zhang¹, Senior Member, IEEE, Wei Li², Member, IEEE, Yiyang Wu³, Fellow, IEEE, Sébastien Lafleche, Zhihong Hong, Sung-Ik Park⁴, Senior Member, IEEE, Jae-Young Lee⁵, Senior Member, IEEE, Heung-Mook Kim, Member, IEEE, Namho Hur⁶, Member, IEEE, Eneko Iradier⁷, Graduate Student Member, IEEE, Pablo Angueira, Senior Member, IEEE, and Jon Montalban⁸, Member, IEEE

Abstract—To meet the ever increasing demand for better service quality and availability, the next generation digital TV (DTV) broadcast, a.k.a., the ATSC 3.0, is developed with new capabilities to deliver 4K ultra-high-definition (4K-UHD) services to fixed receivers, robust HD-quality services to mobile receivers, as well as non-broadcast services (e.g., broadband), including Internet of Things (IoT), Connected Vehicles, etc. To realize these capabilities, it becomes necessary to evolve the existing single-transmitter high-power-high-tower (HPHT) network to multi-transmitter low-power-low-tower single-frequency-networks (SFN), which requires installing new transmitters. Each new transmitter needs a feederlink to receive the service data from the broadcast gateway (BG) for transmission. This feederlink contributes to a significant portion of installation and operational costs of the new transmitters. This paper proposes a wireless in-band distribution link (WIDL) technology, where the distribution data is delivered to the newly deployed transmitters from the existing DTV towers wirelessly sharing the same TV band with the broadcast services. The distribution signal is multiplexed with service signal in the same ATSC 3.0 waveform. Layered division multiplexing (LDM) technology is proposed to achieve more efficient transmission of the distribution signal. The WIDL offers better performance and more robust operation than the on-channel repeater (OCR) technologies. More importantly, it offers the possibility of delivering backhaul data for future applications over the DTV infrastructure, such as IoT and connected vehicles. Therefore, the proposed WIDL is one enabling technology

to achieve convergence of broadcast services with broadband and other wireless services on the DTV spectrum.

Index Terms—In-band distribution, in-band backhaul, layered division multiplexing, LDM, Digital TV, ATSC 3.0, relay, mesh network, full-duplex transmission.

I. INTRODUCTION

TO MEET the fast increasing demand for wireless communication services, a majority of efforts in 5G development have been put on developing technologies to be used at millimeter-wave (mmWave) frequencies, where a vast amount of spectrum is available. On the other hand, sub-1GHz bands, including the UHF spectrum currently allocated for TV broadcasting services, offers many advantages over the mmWave frequencies due to the low propagation loss, high penetration capability, as well as low device costs [1]. These benefits make the sub-1GHz bands better choices to deliver some key future wireless applications including the Internet of Things (IoT), the connected vehicles, the public safety and emergency alert systems, the ultra-robust communications, the multicast/broadcast services, etc.

This offers new business opportunities for the broadcast industry if they can use the UHF bands to deliver more diversified services in addition to TV broadcasting. However, to materialize the business opportunities, the existing DTV technologies and DTV network infrastructures need to be upgraded, and the spectrum regulation and policies also need to be revised.

Currently, the TV broadcasting industry is facing multiple challenges: the reduced spectrum, emerging of many other media delivery platforms over the Internet, shifting of consumer viewing patterns to more on-demand services, etc. To address these challenges and to benefit from new emerging business cases, the next generation DTV system has been developed, which is also called the ATSC 3.0 system [2]. Taking advantage of the latest transmission and video technologies, with Internet Protocol (IP) based transport layer, the ATSC 3.0 system is capable of delivering high-definition (HD)

Manuscript received February 7, 2020; revised April 4, 2020; accepted April 10, 2020. Date of publication May 14, 2020; date of current version March 4, 2021. This work was supported by the Institute of Information and Communications Technology Planning and Evaluation grant Funded by the Korea Government (MSIT) (Development of Transmission Technology for Ultra High Quality UHD) under Grant 2017-0-00081. (Corresponding author: Liang Zhang.)

Liang Zhang, Wei Li, Yiyang Wu, Sébastien Lafleche, and Zhihong Hong are with the Department of Wireless Communications, Communications Research Centre Canada, Ottawa, ON K2H 8S2, Canada (e-mail: liang.zhang@canada.ca; wei.li@canada.ca; yiyang.wu@ieee.org; sebastien.lafleche@canada.ca; zhihonghunter.hong@canada.ca).

Sung-Ik Park, Jae-Young Lee, Heung-Mook Kim, and Namho Hur are with the Broadcasting System Research Department, Electronics and Telecommunications Research Institute, Daejeon 305-700, South Korea (e-mail: psi76@etri.re.kr; jaeyl@etri.re.kr; hmkim@etri.re.kr; namho@etri.re.kr).

Eneko Iradier, Pablo Angueira, and Jon Montalban are with the Department of Communications Engineering, University of Basque Country, 48940 Bilbao, Spain (e-mail: eneko.iradier@ehu.es; pablo.anguera@ehu.es; jon.montalban@ehu.es).

Digital Object Identifier 10.1109/TBC.2020.2989638

mobile services, ultra-HD (UHD) fixed services, interactive services, datacasting services, and can be readily integrated with 4G/5G broadband systems at the network level. More specifically, the high-throughput, flexible program channel configuration, and the IP-based transport layer makes the ATSC 3.0 an excellent candidate to deliver applications such as IoT and connected vehicles over large coverage areas.

The current generation DTV system in North America, the ATSC 1.0 system, uses single-transmitter high-power-high-tower (HPHT) network structure, where a single high-power transmitter is deployed at a high elevation to cover the target coverage area. This infrastructure, while works well for receivers with rooftop antennas, cannot deliver reliable services to mobile receivers that are frequently facing challenging reception conditions, including high-speed vehicle receivers, handheld devices, and receivers in indoor environments.

A good alternative to deliver reliable mobile services is the single-frequency-network (SFN) based on low-power-low-tower (LPLT) infrastructure [3], [4]. In an SFN, multiple transmitters emit the same signal in a time-synchronized and frequency-locked manner. Receivers, especially those close to the boundaries among adjacent coverage areas, can effectively combine the multiple signals received from adjacent transmitters. This results in a better reception performance due to the spatial diversity, which is also called an SFN gain.

Implementing an SFN requires deploying new transmitters, where each transmitter needs a distribution link, also called studio to transmitter link (STL), to obtain the service data from a Broadcast Gateway (BG) for transmission. The STL is also responsible for sending control signal to each SFN transmitter (SFN-Tx) to apply specific timing and frequency offsets to optimize the coverage performance.

Until now, the STL links are implemented using either fiber links or dedicated microwave links. Fiber links are not always available for locations to deploy SFN transmitters. Even if it is available, the cost to rent a fiber link is quite expensive. The dedicated microwave link is also quite expensive to install. In addition, with the current trend of allocating more spectrum for consumer broadband systems, the microwave spectrum becomes less available for distribution data transmission. Therefore, using either of these conventional STL methods would introduce significant cost from both initial installation and monthly operation. This cost quickly becomes unaffordable for SFNs with large number of low-power transmitters. Consequently, a cost-efficient solution is needed for the SFN deployment of the emerging ATSC 3.0 system.

Another important scenario is to deliver services to indoor or enclosed places within a coverage area that are difficult for wireless signals to reach, such as shopping malls, train stations, airport, stadiums, etc. These areas, however, provide good commercial opportunities for broadcasters due to the high density of headcounts. An efficient solution to provide robust services to these enclosed areas is to deploy gap-fillers, i.e., very low-power re-transmitters. To be economically

viable, the gap-fillers need to be very low-cost, since they are used to cover only a small area. Neither fiber link nor the microwave link is suitable solution due to their high cost. This scenario also calls for low-cost STL solutions.

Thanks to the latest video coding and transmission technologies, the newly developed ATSC 3.0 system could deliver significantly high throughput. This offers the opportunity to use part of the TV channel to transmit the distribution data while still delivering same or more mobile and fixed broadcast services than the current ATSC 1.0 system.

In this paper, a wireless in-band distribution link (WIDL) solution is proposed, where the distribution data is transmitted from an existing transmitter, also called Master Transmitter (MTx), to the newly installed SFN-Tx's, using the same TV band for broadcast service transmission. In the proposed approach, the STL is integrated into the ATSC 3.0 signal emitted from the MTx as a special non-broadcasting service, which can only be decoded by the SFN-Txs. Therefore, the STL and the broadcast services are sharing the same TV band, and hence called an in-band distribution solution.

In the proposed WIDL, since the STL data is multiplexed with the service data over the same time-frequency resource, the achievable throughput of broadcast services is reduced. To minimize the service throughput loss, the non-orthogonal layered-division-multiplexing (LDM) technology is proposed to multiplex the STL data and the broadcast service data over a single TV channel, due to its significant capacity advantage over the traditional orthogonal time-domain multiplexing (TDM) and frequency-domain multiplexing (FDM) [5].

Since the proposed technology delivers the STL in a special logical channel, also called physical layer pipe (PLP) in ATSC 3.0, the WIDL equipment shares many system modules with conventional ATSC 3.0 equipment. This significantly reduces the engineering effort and implementation cost.

A similar concept has been studied for mobile broadband systems in [6], where the distribution data is called backhaul data. The 4G Long Term Evolution Advanced (LTE-A) system adopted integrated access and backhaul (IAB) technology to implement low-cost backhaul links to relay nodes (RNs) [7]. The backhaul transmission can operate in either in-band or out-of-band modes. In in-band mode, the backhaul transmission and service transmission share the same spectrum; while in out-of-band mode, the backhaul data is transmitted using a separate spectrum. Apparently, the in-band mode is more attractive since there is no need to apply for dedicated backhaul channels. However, it also means that the service throughput will be reduced to accommodate the backhaul transmission.

The RNs could operate in either half-duplex mode or full-duplex mode. In half-duplex mode, at any given time, an RN either receives the backhaul signal or transmits the service signal; while in full-duplex mode, the RN performs these two operations simultaneously. It becomes obvious that full-duplex mode offers a clear throughput advantage over the half-duplex mode. However, full-duplex mode creates self-interference issue that requires careful design and advanced

signal processing algorithms to obtain good backhaul signal detection. This results in increased implementation complexity.

Therefore, to achieve the highest system throughput, the in-band full-duplex is the most attractive solution. Up until now, all the in-band full-duplex IAB solutions adopted by LTE use orthogonal multiplexing (OM) methods, such as TDM and FDM to combine the service and backhaul data within the same channel [8]. Spatial domain multiplexing (SDM) was proposed in some recent works to reduce the interference between the service and backhaul signals [9].

OM technologies have been the preferred multiplexing technologies by earlier systems due to the simplicity in the receiver implementation. When using OM, there is little interference between the service and backhaul signals. On the other hand, it has been proved that OM technologies are far from achieving channel capacity for multiple signal transmissions over the same frequency resource [10].

In [11], a wireless distribution link was first proposed for the newly developed ATSC 3.0 system. The proposed technology targeted low-power gap-fillers to provide mobile broadcast services to large public enclosed areas, such as airports, train stations, stadiums, etc. This concept is later expanded to a fully backward compatible WIDL solution in [12] that can deliver distribution data to general high-power SFN transmitters. In [13], this technology is adapted for the deployment of a 5G-Broadcast network.

To the best knowledge of the authors, using wireless distribution links for broadcast services has never been studied prior to the work presented in [11].

This paper presents further development of the WIDL technology in ATSC 3.0 system. A complete distribution link solution is proposed, which uses LDM, multiple-input-multiple-output (MIMO) and other latest technologies to minimize the capacity loss of the service transmission. Different WIDL implementation options are discussed with their respective capacity-complexity trade-offs. Achievable system capacities are analyzed for different system configurations. Feasibility study is conducted at the SFN transmitters and implementation challenges are addressed. Finally, a future extension to a mesh distribution network is also discussed that could provide more network fault tolerance for large-area SFN with many transmitters.

There is currently a global trend on convergence of different wireless communications systems to achieve more efficient use of the spectrum and the infrastructure. The deployment of the IP-based ATSC 3.0 using medium-size cells is the approach for convergence from the broadcast industry. The proposed WIDL technology could play a critical role to enable quick deployment of new ATSC 3.0 systems and to deliver new types of services.

It needs to be pointed out that the proposed WIDL technology can deliver broadcast and different non-broadcast distribution data to each SFN transmitter. This is the key difference between the WIDL and the existing on-channel repeaters (OCR), which are designed to solely expand the coverage area. Therefore, using WIDL would offer broadcasters business opportunities to use ATSC 3.0 infrastructure and the TV spectrum to deliver broadband and other wireless services.

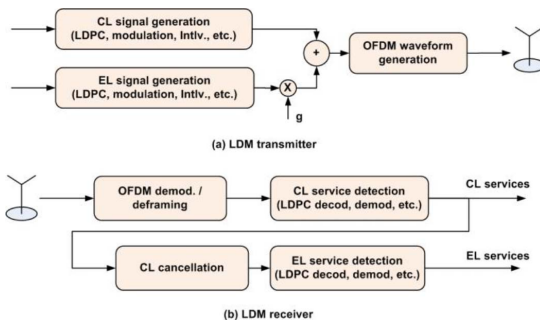


Fig. 1. ATSC 3.0 with a 2-layer LDM.

This paper is organized as follows: Section II briefly describes the concept of the WIDL solution in ATSC 3.0 systems with LDM, different signal configurations, and the achievable transmission capacities when different technologies are used. Section III presents an analysis on the achievable throughput of WIDL. In Section IV, challenges for detecting WIDL signal at the SFN transmitters are discussed and solutions are proposed. Section V describes a case study in Ottawa area to demonstrate the feasibility of the proposed WIDL technology for a wide range of ATSC 3.0 system configurations. Section VI proposes potential future evolutions of the WIDL technology. Section VII focuses on a comparison between the WIDL solution and the OCR technology. Finally, Section VIII gives the conclusions.

II. WIRELESS IN-BAND DISTRIBUTION LINKS IN ATSC 3.0

A. ATSC 3.0 and LDM

As a new generation DTV system, ATSC 3.0 uses the latest high efficiency video coding (HEVC) and advanced transmission technologies, including improved low-density-parity-check (LDPC) code [14], non-uniform QAM (nuQAM) modulation [15], MIMO [16], and LDM [5]. While most of these technologies provides only marginal performance improvement, LDM has been shown to offer significant service capacity gain.

LDM is a non-orthogonal multiplexing (NOM) technique that was adopted by ATSC 3.0, to provide significantly higher throughput when delivering services with different quality of service (QoS) requirements over the same channel [5]. In LDM, multiple signal layers are transmitted over the same time and frequency radio resource, where each signal layer delivers services with a specific QoS requirement.

The block diagrams of ATSC 3.0 transmitter and receiver with a 2-layer LDM are shown in Figure 1. At the transmitter, two signal layers are first generated separately, which are subsequently combined with a pre-defined power ratio, determined by the coefficient g . The higher-powered layer is called Core Layer (CL), while the lower-powered layer is called Enhanced Layer (EL). At the receiver, conventional signal

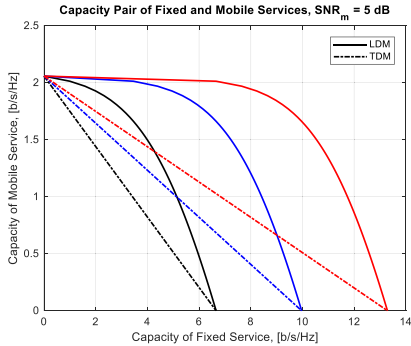


Fig. 2. LDM capacity gain over TDM.

detection is carried out to decode the CL services, treating the EL as interference. To decode the EL services, the receiver first decodes and cancels the CL signal, and then performs conventional signal detection. Canceling CL signal is called successive signal cancellation (SSC), which is the main additional signal processing required at an LDM receiver [5].

Figure 2 compares the achievable service capacities of a 2-layer LDM system and a TDM system, where both systems deliver two services: a robust service requiring a low signal to noise ratio (SNR) of 5 dB and a fixed service requiring a high SNR of 20, 30, or 40 dB. The LDM system uses CL for mobile service delivery and EL for fixed service delivery, while the TDM counterpart uses different time slots for the two services.

It is clearly shown that LDM offers significantly higher capacity than the TDM system. This capacity gain becomes higher for fixed services with higher SNR requirements, i.e., higher fixed service throughput.

The achievable capacities of ATSC 3.0 with LDM has been demonstrated by theoretical analysis, computer simulations and field tests [17]. With LDM, an ATSC 3.0 system could simultaneously deliver four to six 1080p high-definition (HD) fixed TV programs and one to two 720p HD mobile programs in one TV channel of 6 MHz, in comparison to only one 1080p HD fixed service delivered by the current ATSC 1.0.

Assuming an ATSC 3.0 system is deployed to deliver two 1080p fixed and two 720p mobile services, which is more than twice the throughput of an ATSC 1.0 system, it still has an additional throughput for 2~4 fixed services in EL. This extra capacity could be used to deliver the distribution data.

Distribution data is delivered between transmission towers, where both the transmitter and the receiver antennas are located on towers at high elevations. This enables very high signal SNR at the distribution data receiver, especially high-gain directional receiving antenna can be installed. As shown in Figure 2, this is an ideal application scenario for using LDM EL, where high SNR brings a high capacity benefit.

B. Wireless in-Band Distribution Links in ATSC 3.0

A traditional ATSC 3.0 network with four transmitters is illustrated in Figure 3. The BG is responsible for sending

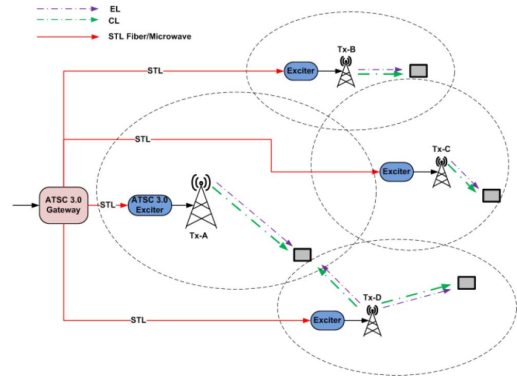


Fig. 3. Traditional ATSC 3.0 SFN.

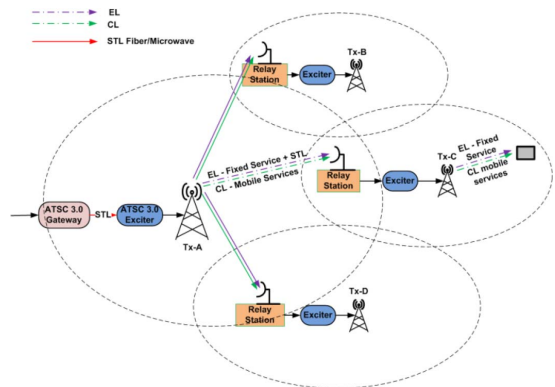


Fig. 4. ATSC 3.0 SFN with wireless in-band distribution.

distribution data to each transmitter via STLs, implemented by fiber links or dedicated microwave links. The distribution data for each transmitter includes both the broadcast service data and specific control signaling that configures the time and frequency offsets for signal emission.

In SFN, all transmitters emit the same signal and the transmissions are time-synchronized and frequency-locked. Therefore, the STLs for different transmitters deliver the same service data. On the other hand, the control signaling is unique for each transmitter, where different time and frequency offsets are applied to different transmitters to achieve a more uniform coverage performance.

The traditional structure suffers not only high installation and operation costs, but also very low efficiency since all the four STLs mostly carry the same service data.

The proposed WIDL solution is shown in Figure 4 for the same ATSC 3.0 SFN with four transmitters. There is one main transmitter with a traditional STL by fiber or microwave link, which will be referred as anchor transmitter (A-Tx) hereinafter. The A-Tx receives its own STL data and the STL data for the other three transmitters, which will be referred to as remote transmitters (R-Tx) in the rest of this paper.

The A-Tx uses its own STL data to generate the broadcast service signal for transmission within its own coverage area. At the same time, the A-Tx will encode the STL data for the three R-Tx's into the same ATSC 3.0 waveform. The STL data would be encoded into PLPs with special service identifications that would only be decoded by the distribution data receivers at the R-Tx's. The consumer receivers would simply ignore the STL PLPs due to the unrecognized service identification. Therefore, the proposed WIDL is fully backward compatible and has no impact on existing services for consumer receivers.

The A-Tx only needs to encode the broadcast service data once in the transmission signal for all three R-Tx's, because the broadcast service data is the same for different transmitters in an SFN. This results in high spectral efficiency. On the other hand, A-Tx needs to transmit all the specific control signaling for all R-Tx's. Fortunately, this won't require much extra capacity since the control signaling requires very little data.

Most likely, the A-Tx would be an existing ATSC 1.0 high transmitter tower, capable of emitting high power. The BG to the A-Tx link is the existing STL for ATSC 1.0 installation.

At an R-Tx, a Relay Station (RS) is implemented to receive and decode the distribution data in the signal from A-Tx. The decoded distribution data is then fed into an Exciter which generates the service signal for emission.

At the R-Tx, the RS receive antenna can be installed at a high elevation on the transmission tower, which results in a line-of-sight (LOS) propagation channel for the distribution signal. In addition, a highly directional receiving antenna could be installed so that the received distribution signal could have very high SNR. These favorable reception conditions make the LDM EL the ideal choice to deliver the STL data. Furthermore, with high received SNR, the in-band distribution signal can be configured using spectral efficient modes, i.e., with higher-order modulations and higher coding rates. Therefore, the spectrum resource required for STL data transmission could be very small and there is no significant reduction in service delivery capacity.

C. Transmitter Timing Control for SFN Operation

In an SFN as shown in Figure 4, all the transmitters need to deliver the same service signal, and the emissions from different transmitters need to be time-synchronized. When using WIDL, this requires that the STL data embedded in the A-Tx transmission signal has a time advance with respect to the service data. This time advance is needed for the R-Tx to receive and decode the STL signal, and to generate the service signal for re-emission. Therefore, a timing control mechanism needs to be designed to configure the relative timing between the STL data and the service data to align the operations of the different transmitters.

The timing control for SFN is illustrated in Figure 5 and explained as follows:

- In the transmission signal from the A-Tx, the STL data, $d(t - T)$, is transmitted with a time advance of T than the service data, $s(t)$.

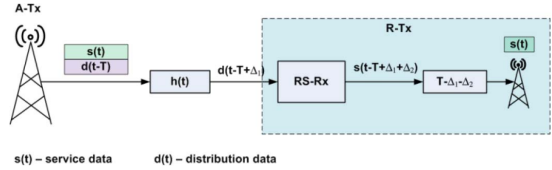


Fig. 5. ATSC 3.0 SFN with wireless in-band distribution.

- At the R-Tx, the RS receives a delayed STL data $d(t - T + \Delta_1)$, where the delay, Δ_1 , is introduced by the signal propagation.
- The RS performs necessary decoding signal processing to recover the STL data and subsequently encoding signal processing to generate the ATSC 3.0 SFN service signal. The output is an ATSC 3.0 signal, $s(t - T + \Delta_1 + \Delta_2)$, which contains the same SFN service signal as that from the A-Tx, with a relative delay of $-T + \Delta_1 + \Delta_2$, where Δ_2 is the time required to decode the STL data and encode the service data.
- To align the service signal from A-Tx and R-Tx, an additional emission adjustment delay of $T - \Delta_1 - \Delta_2$ is further introduced so the emission service signal from the R-Tx is synchronized to that from A-Tx, i.e., $s(t)$.

It becomes obvious that the time-advance of the STL data, T , needs to be at least as long as the sum of the two delays, $(\Delta_1 + \Delta_2)$. While the propagation delay, Δ_1 , is usually quite small, the signal processing delay, Δ_2 , could be fairly long since it involves two interleaving/deinterleaving processes. Δ_2 could be expressed as,

$$\Delta_2 = \Delta_{STL-DeIntlv} + \Delta_{SER-Intlv} + \Delta_{res} \quad (1)$$

where $\Delta_{STL-DeIntlv}$ and $\Delta_{SER-Intlv}$ are the delays introduced by the deinterleaving for STL decoding and the interleaving for service signal encoding, respectively, and Δ_{res} is the delay introduced by all the other signal processing components.

Since STL signal transmission faces near LOS channel and high SNR conditions, it is possible to use a short time-domain interleaver, or even disable it. Therefore, $\Delta_{STL-DeIntlv}$ could be a small delay as well.

The length of $\Delta_{SER-Intlv}$, however, could vary significantly depending on what type of services the STL data is used for. For fixed services, this delay could be a fraction of an ATSC 3.0 frame length. For extremely robust mobile services, the time-domain interleaver could cover multiple frames and the delay could be multiple ATSC 3.0 frame durations. This is, however, a rare case in actual deployments.

In typical service scenarios, a time-advance of one ATSC 3.0 frame duration is sufficient for SFN operation.

III. WIDL THROUGHPUT ANALYSIS

There are different signal structures to integrate the STL signal and the service signals into one ATSC 3.0 waveform. In this section, the WIDL throughput requirement is analyzed for different broadcast service scenarios.

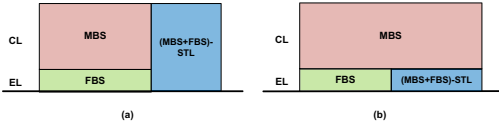


Fig. 6. WIDL signal models for both mobile broadcast service (MBS) and fixed broadcast service (FBS) distribution: (a) TDM; (b) LDM.

TABLE I
EXAMPLES OF WIDL SCENARIOS WITH TDM AND LDM

		WIDL (%)	MBS [Mbps]	FBS [Mbps]	STL [Mbps]
STL-SISO	TDM	33%	2.6	10.7	13.4
	LDM	41%	4.0	9.5	13.5
STL-MIMO	TDM	20%	3.2	12.8	16.0
	LDM	24%	4.0	12.1	16.1
No WIDL		0%	4.0	16.0	0

A. Multiplexing of Distribution and Service Signals

Two WIDL signal configurations are plotted in Figure 6, where the STL data is multiplexed with the service data using TDM (STL-TDM) and LDM (STL-LDM), respectively. Figure 6(a) shows the TDM configuration where the STL signal is assigned to a single-layer PLP. For the LDM configuration in Figure 6(b), the STL data is delivered in an LDM-EL PLP. The STL data contains service data for both mobile broadcast services (MBS) and fixed broadcast services (FBS).

Comparing these two configurations, the STL-TDM uses a higher power to transmit the STL data and therefore will have a higher SNR at the R-Tx, making it easier to decode. In addition, the STL-TDM requires low-complexity receivers at the R-Tx, since no SSC is needed to decode the STL data.

In comparison, the STL-LDM provides a higher mobile service capacity in the CL, as shown in Figure 6. Since the mobile services need to use strong coding and modulation to cope with the various fading conditions, they usually have lower bit rate. To keep the good QoE on mobile service, it is therefore desirable not to lose any mobile capacity.

The STL PLP throughput should be higher than the combined throughput of all service PLPs. This can be expressed as,

$$\begin{aligned} R_{STL} &= R_{MBS} + R_{FBS} + R_{ctrl} \\ &\cong R_{MBS} + R_{FBS} \end{aligned} \quad (2)$$

where R_{ctrl} is required for SFN control signaling.

Let's assume an original ATSC 3.0 system delivering two 720p-HD mobile service in CL and four 1080p-HD fixed services in EL. In TABLE I, the STL throughput and the service throughput are listed for both STL-TDM and STL-LDM, assuming a mobile service PLP with QPSK and rate-6/15 LDPC, a fixed service with 64QAM and rate-8/16 LDPC, and the STL PLP with 1k-QAM and rate-12/15 LDPC.

It is shown that using STL-LDM could keep the full MBS capacity of 4.0 Mbps, where using STL-TDM results in a 35% MBS capacity loss. On the other hand, for FBS services, using STL-LDM suffers a capacity loss of 11%.

MIMO technology could be applied to increase the spectral efficiency of the STL link [16]. Since the propagation model for the STL link is close to LOS channel, the most effective option is to use dual-polarized 2x2 MIMO. With the favorable SNR condition of the STL link, it is possible to achieve doubled capacity and significantly reduce the required radio resource for STL transmission.

TABLE I. also shows the transmission throughputs when MIMO is applied to the STL link. With MIMO, much smaller time percentage needs to be allocated for STL transmission. It is shown that using STL-LDM has a mobile service capacity gain of 25% over STL-TDM, and a fixed service capacity loss of 5.5%.

In TABLE II, some practical use cases for the STL-LDM signal configuration are listed. In all scenarios, a mobile service of HD-1080p is always delivered in CL. In EL, different scenarios are considered that deliver multiple full-HD services, a 4k-UHD, or the enhancement layer for a service with scalable-video coding, each requiring different throughput. For service delivery, it is assumed both the transmitter and the receiver have only one antenna, i.e., single-input-single-output (SISO), which is the typical commercial case. For STL link, both SISO and 2x2 MIMO are considered.

The first three scenarios in TABLE II. clearly show that the high transmission throughput available from ATSC 3.0 makes it feasible to transmit many mobile and fixed broadcast programs, and their STL data, in a single 6 MHz TV channel. These scenarios are also important for transition from ATSC 1.0 to ATSC 3.0, where one tower needs to transmit multiple programs from different broadcasters in one ATSC 3.0 signal.

It is shown that, even for delivering two (2) 720p-HD mobile service and one 4k-UHD fixed service (or four to six 1080p-HD fixed services simultaneously), it is possible to use 40% of the time allocation to transmit the distribution data within the same ATSC 3.0 signal, with a single antenna on both A-Tx and R-Tx. However, high SNR is required at R-Tx since large constellation and high coding rate need to be used.

With 2x2 MIMO, a time allocation of less than 30% could be used to deliver the distribution data, for the same scenarios. The SNR requirements becomes much lower since 256QAM and rate-10/15 LDPC code could be used.

For a second scenario where only the STL data of mobile services is delivered using WIDL to gap-fillers for indoor public areas or R-Tx's in remote areas, only a small percentage of time is required for the STL transmission. The STL-TDM and STL-LDM solutions for this scenario are plotted in Figure 7; while the required STL signal configurations for different time allocations are calculated, for two mobile service qualities of 720p (2.7 Mbps) and 1080p (4.1 Mbps).

It is observed that, to deliver STL data for mobile service only, a time percentage of only 5 ~ 10% is needed.

IV. IN-BAND DISTRIBUTION SIGNAL DETECTION

Figure 8 shows a block diagram of the STL signal detection at an R-Tx. The received signal from the A-Tx contains both the SFN service component (MBS+FBS) and the STL component. This signal will be referred to as forward signal (FWS)

TABLE II
IN-BAND BACKHAUL SCENARIOS FOR MIXED MOBILE AND FIXED SERVICES

Scce.	Mobile Service (SISO)	Fixed Services (SISO)		STL Configuration		
				SISO TDM-40%	2x2 MIMO TDM-30%	2x2 MIMO TDM-20%
1*	4.1 Mbps (2~3) x 720p/30fps or (6~8) x 480p/30fps	8.2 Mbps		12.3 Mbps	12.3 Mbps	12.3 Mbps
		(4~6) x 720p/60fps	(2~3) x 1080p/60fps	1k-QAM, L-9/15	256QAM, L-8/15	1k-QAM, L-9/15
2*	1.8 Mbps 1 x 720p/30fps or 3 x 480p/30fps	12.3 Mbps		16.4 Mbps	16.4 Mbps	16.4 Mbps
		(6~9) x 720p/60fps	(3~5) x 1080p/60fps	1k-QAM, L-12/15	256QAM, L-10/15	1k-QAM, L-12/15
3*	3.4 Mbps 1080p SHVC-BL	16.4 Mbps		20.5 Mbps	20.5 Mbps	20.5 Mbps
		(8~12) x 720p/60fps	(4~6)x1080p/60fps	4k-QAM, L-11/15	1k-QAM, L-9/15	4k-QAM, L-11/15
4	10.1 Mbps 4k-UHD SHVC-EL	10.1 Mbps		13.5 Mbps	13.5 Mbps	13.5 Mbps
				1k-QAM, L-10/15	256-QAM, L-9/15	1k-QAM, L-10/15

* A 30% statistical multiplexing gain is assumed.

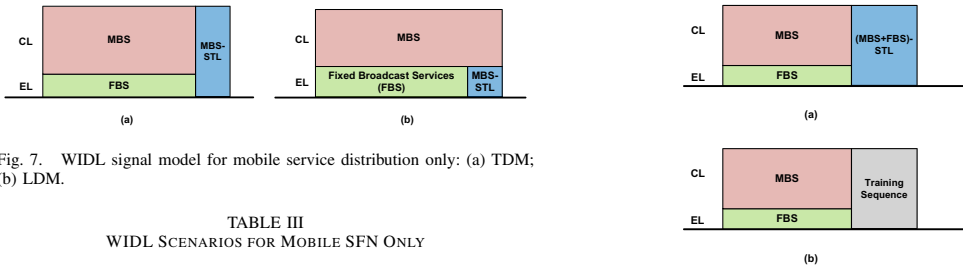


Fig. 7. WIDL signal model for mobile service distribution only: (a) TDM; (b) LDM.

TABLE III
WIDL SCENARIOS FOR MOBILE SFN ONLY

Scce.	R_{mob} (Mbps)	STL Signal Configuration				
		50%	25%	15%	10%	5%
1	2.7	16Q	16Q	64Q	256Q	1k-Q
		4/15	7/15	9/15	8/15	13/15
2	4.1	16Q	64Q	256Q	1k-Q	NA
		6/15	8/15	10/15	12/15	

Fig. 9. Signal model at RS-Rx; (a) FWS; (b) LBS.

transmission antenna are usually installed on the same tower and both at high elevations, they are closely located. This results in a very high LBS signal power received at the RS-Rx receive antenna.

In Figure 9, the structures of the FWS and LBS signals received at the RS-Rx antenna are illustrated for an ATSC 3.0 SFN system with WIDL using STL-TDM. In the FWS, MBS and FBS are delivered in a two-layer LDM configuration in a specific time slot, while the STL data for both services is delivered in a different time slot.

During the time slot allocated for broadcast services, the LBS is the same as the FWS, because A-Tx and R-Tx delivers synchronized SFN services. However, during STL time slot, the FWS and LBS are different. Therefore, the LBS becomes a strong interference to the STL detection at the RS-Rx. This interference is also called self-interference in the in-band full-duplex relay for LTE/5G [18].

For OFDM-based ATSC 3.0 system, the received signal at the RS-Rx during the STL time slot can be expressed as,

$$Y_{RL}(k) = X_{STL}(k) \cdot H_{FWS}(k) + \sqrt{\kappa_{LBS}} \cdot X_{LBS}(k) \cdot H_{LBS}(k) + N_0(k) \quad (3)$$

where $X_{STL}(k)$ and $X_{LBS}(k)$ are the FWS and LBS symbols in the k^{th} subchannel, $H_{FWS}(k)$ and $H_{LBS}(k)$ are the channel responses of the forward and loopback channels, κ_{LBS} is the power ratio of the LBS over FWS, and $N_0(k)$ is the thermal noise.

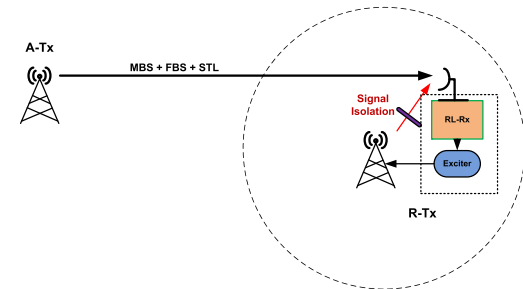


Fig. 8. Backhaul signal detection at RS-Rx.

for the rest of this paper. At the R-Tx, the RS-Rx decodes the STL data, from which the SFN service signal is generated and fed into the Exciter for emission. To achieve high SNR condition for the STL data detection, a powerful directional antenna is usually installed at the RS-Rx.

Figure 8 also shows a design challenge at the RS-Rx for STL detection. The RS-Rx receiver not only receives the FWS from the A-Tx, but also picks up the emission signal from the R-Tx transmission antenna, which is called loopback signal (LBS). Since the RS-Rx receive antenna and the R-Tx

Ideally, the self-interference could be removed if the R-Tx could transmit zero power during the STL time slot. This, however, is not allowed in the ATSC 3.0 standard. Even if allowed, this option is not desirable since part of the transmission capacity is wasted at the R-Tx, which can be used to deliver local services or STL to a subsequent R-Tx. When the R-Tx does not transmit service within the STL time slot, it needs to insert dummy symbols. Therefore, the RS-Rx needs to cope with the LBS self-interference to decode the STL data.

The impact of the LBS self-interference directly depends on the relative power ratio of the LBS over the FWS, κ_{LBS} , which depends on the A-Tx transmission power, the propagation distance from the A-Tx to the R-Tx and the R-Tx emission power. This results in a very large range of κ_{LBS} value. For a low-power SFN gap-filler (R-Tx) and a high-power A-Tx, κ_{LBS} could be quite small (close to 0 dB); while for a full-power R-Tx, κ_{LBS} could be well over 120 dB.

When the LB signal power is very high, it could easily saturate the RS-Rx's radio frequency (RF) front end (RFFE) and completely disable the RS-Rx operation.

To reduce the impact of the LBS on the STL signal detection, the RS-Rx could implement signal isolation mechanism between the transmit and receive antennas, followed by signal cancellation algorithm in the RS-Rx receiver.

A signal isolation (SI) mechanism could be designed to reduce the LBS power received by the RS-Rx antenna, as shown in Figure 8. Effective signal isolation could be achieved by antenna spacing, blocking, receive antenna shielding, and antenna directivity design. It has been shown that signal isolation of 70-100 dB could be achieved in practice [19], [20].

With the SI, the received signal at the RS-Rx becomes,

$$Y_{RL}(k) = X_{STL}(k) \cdot H_{FWS}(k) + X_{LBS}(k) \cdot H_{LBS}(k) + N_0(k) \quad (4)$$

For an R-Tx that emits medium to high power levels, even with a significant isolation, the residual LBS power could still be 10 to 20 dB higher than the received FWS, especially when the A-Tx is far away from the R-Tx. To further reduce the LBS component in (4), signal cancellation algorithm is carried out in the RS-Rx receiver as,

$$Y_{STL}(k) = Y_{RL}(k) - X_{LBS}(k) \cdot \hat{H}_{LBS}(k) = X_{STL}(k) \cdot H_{FWS}(k) + \gamma_{LBS} + N_0(k) \quad (5)$$

where \hat{H}_{LBS} is the loopback channel (LBCH) estimate.

In (5), γ_{LBS} is the residual LBS signal after the signal isolation and signal cancellation, whose variation is calculated as,

$$\sigma_{LBS}^2 = E \left\{ \left| H_{LBS} - \hat{H}_{LBS} \right|^2 \right\} = v_{H-LBS}^2 \quad (6)$$

where v_{H-LBS}^2 is the mean square error (MSE) of the LBS channel estimate.

Therefore, the critical system components at the RS-Rx are the signal isolation and the signal cancellation modules.

A. Loopback Signal Isolation

The objective of the SI is to minimize the LBS power arriving at the RS-Rx receive antenna. This can be achieved by several approaches:

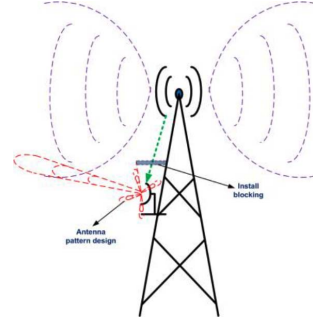


Fig. 10. Loopback signal isolation methods at R-Tx.

- 1) *Increasing the Antenna Spacing*: At the R-Tx, both the RS-Rx receive antenna and the transmit antenna are installed on the same tower at high elevations. The loopback signal propagation channel between these two antennas should be a LOS channel. The distance between them is at most a few hundred meters. For this distance, the propagation loss could be well modeled as free space path loss (FSPL), which is calculated as,

$$FSPL(dB) = 20 \log(d) + 20 \log(f) + 32.44 \quad (7)$$

where d is the distance in km , f is the frequency in MHz . Therefore, an antenna distance of 100 meters gives a LBS power 20 dB lower than that from a distance of 10 meters.

- 2) *Loopback Signal Blocking*: A metal shielding could be installed above the RS-Rx receive antenna, as shown in Figure 10. This is especially useful for some antennas with small form factors, such as the panel antennas. In [20], a metal mesh installed on top of a panel antenna is shown to be quite effective to block the loopback signal.
- 3) *Receive Antenna Directivity*: Modern antenna design could be applied on the receive antenna to have a Null towards the transmission antenna, further reducing the LBS power. However, this may require installation of multiple antenna elements and more engineering effort and larger space on the tower.

B. Loopback Signal Cancellation

To cancel the loopback signal as (5), the RS-Rx first needs to estimate the LBCH, H_{LBS} . To reduce the amount of radio resources required for STL data delivery, it is desirable to use high-throughput signal configuration for the STL signal, i.e., high-order modulation, high coding rate, MIMO, etc. This requires high SNR to decode and puts a high requirement on the LBCH estimation accuracy.

Because the RS-Rx knows exactly what signal is being transmitted during the STL time slot, as shown in Figure 9, the loopback channel can be estimated using decision-directed channel estimation (DD-CE) algorithms.

To perform DD-CE, the frequency-domain (FD) least square (LS) channel estimation is first obtained as,

$$\begin{aligned} \tilde{H}_{LBS}(k) &= \frac{Y_{RL}(k)}{X_{LB}(k)} \\ &= H_{LBS}(k) + \frac{X_{STL}(k) \cdot H_{FWS}(k) + N_0(k)}{X_{LB}(k)} \end{aligned} \quad (8)$$

where the received forward signal from A-Tx.

A two-dimensional filtering (2D-Filt) could be used to enhance the channel estimation accuracy. A frequency-domain filter (FD-Filt) is first applied on the LS estimates,

$$\hat{H}_{LBS-FD} = \Psi_F \{ \tilde{H}_{LBS} \} \quad (9)$$

where Ψ_F could be a minimum mean square error (MMSE) filter [21], a singular value decomposition (SVD)-based filter [22], a DFT-Filter [23], a Wiener filter, or simply a smooth windowing function.

A time-domain (TD) filter is subsequently applied to further improve the accuracy of the channel estimate:

$$\hat{H}_{LBS-2D} = \Psi_T \{ \hat{H}_{LBS-FD} \} \quad (10)$$

where Ψ_T is usually a Wiener filter or a smooth windowing.

Computer simulations were conducted to evaluate the achievable LBS cancellation performance, assuming a low-complexity DD-CE with 2D-Filt, which consists of a FD Wiener filter followed by a TD average windowing.

Since the STL receive antenna and the R-Tx transmit antenna are installed on the same tower and are closely located, the LBCH could be well approximated by a LOS channel. However, for cases where there are some obstacles surrounding the R-Tx tower, the LBCH could be modeled as a multipath channel with very short delay spread. Therefore, two channel models are tested in simulations, a typical LOS channel and a rare multipath channel, which is modeled as a Typical Urban [24] channel with a mean delay spread (DS) of $0.1 \mu\text{sec}$, and a maximum DS of $0.7 \mu\text{sec}$.

An ATSC 3.0 system with 16k transmission mode is used in simulations. It is assumed that the forward signal has an SNR of 25 dB at the RS-Rx receiver. Four LBS/FWS power ratios, [0 10 20 30] dB, are tested to evaluate the LBS cancellation performance under a wide range of operational conditions. Since the power ratio is for LBS after the signal isolation, a 30 dB of LBS/FWS is a rather pessimistic condition.

Figure 11 shows the LBS cancellation performance for a LOS channel. In this case, the Wiener filter in frequency-domain becomes an averaging window, where a window size of 500 taps is used. In time-domain, an averaging window of 40-taps is used. The upper subplot shows the MSE of the channel estimation after the 2D-Filt, while the lower subplot shows the SNR of the STL signal after the LBS cancellation.

For LOS channels, for all LBS/FWS power ratios, using this simple 2D channel estimator could achieve a residual loopback signal power of more than 40 dB lower than the FWS signal. Considering that the required SNR for high-throughput STL signal in the FWS is usually from 25 to 30 dB, this LBS cancellation performance is more than sufficient.

Figure 12 shows the LBS cancellation performance in a more challenging short TU channel, which could serve

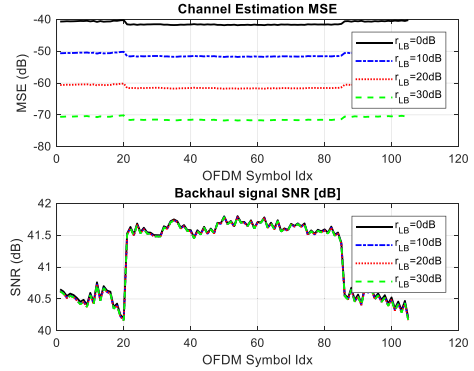


Fig. 11. LBS cancellation performance, LOS channel.

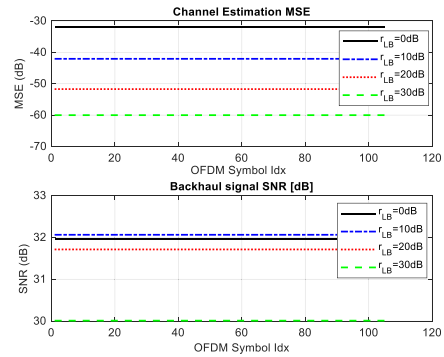


Fig. 12. LBS cancellation performance, short TU channel.

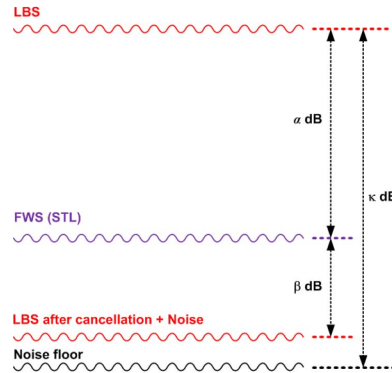


Fig. 13. RS-Rx dynamic range requirement.

as a worse-case scenario. Due to the frequency selectivity, a Wiener filter of 50-tap is used in frequency-domain and a large time-domain windowing of 100 taps is used.

Even for this multipath channel, for all scenarios, the loopback signal cancellation can reduce the LBS signal power to be 30 dB lower than the FWS signal, which is still enough for STL detection requiring an SNR of 25 dB.

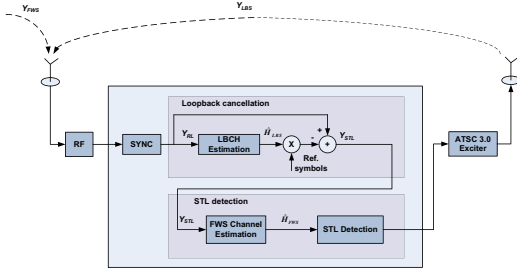


Fig. 14. RS-Rx receiver block diagram, WIDL-TDM.

It needs to be pointed out that the loopback signal only impacts the backhaul signal reception. It has absolutely no impact on the broadcast service reception by the ATSC 3.0 consumer receivers. The backhaul signals are simply ignored by the consumer receivers.

C. RS-Rx Dynamic Range Requirement

The previous analysis assumes that the RS-Rx has sufficient dynamic range to receive a signal consists of both the FWS and the LBS. When the power of LBS is much higher than that of FWS, the required dynamic range is also increased.

The dynamic range requirement of the RS-Rx is illustrated in Figure 13. Assuming the LBS is α dB higher than the FWS and the required SNR to decode the STL signal is β dB, the dynamic range of the RS-Rx, κ , should be larger than $\alpha + \beta$.

For example, for an LBS/FWS power ratio of 30 dB and a required SNR of 25 dB for STL detection, the receiver needs to have a dynamic range of at least 55 to 60 dB. While this is not impossible, it is quite challenging to implement.

To reduce the dynamic range requirement, the LBS power level needs to be reduced. This can be achieved by designing a more effective SI module using the technologies mentioned in Section IV-A. If an advanced SI module could lower the LBS power by 15 dB, the required receiver dynamic range becomes 45 dB for the above example. This is quite achievable for professional equipment.

A second solution to lower the LBS power at the receiver tuner input is to implement an analog LBS signal cancellation module, as proposed for on-channel repeaters (OCR) in [25]. The proposed method can reduce the LBS signal strength by up to 50 dB. The cost is the additional complexity.

It should be pointed out that for most multi-cell deployment scenarios, the emission power from the R-Tx is much lower than the A-Tx. With a good SI mechanism, an LBS/FWS power ratio of 30 dB is highly unlikely to occur. A reasonable range is from 0 to 15 dB.

D. STL Receiver Structure at R-Tx

A detailed receiver block diagram of the RS-Rx is plotted in Figure 14 for WIDL using TDM, which was shown in Figure 9. There are two major components in this receiver: the LBS cancellation module and the STL signal detection module. Two channel estimation (ChEst) modules are needed:

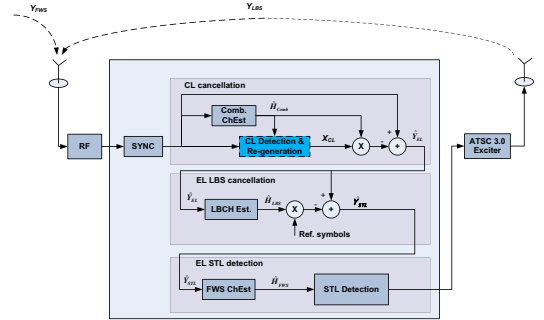


Fig. 15. RS-Rx receiver block diagram, WIDL-LDM.

TABLE IV
DTV CHANNELS FOR MEASUREMENT

Ch.	Ch. #	Fc [MHz]	H _{Tx} * [m]	Tx ERP [dBm]
Global Toronto	14	473	169.1	81.6
TVO	24	533	130.9	79.8
CBC Ottawa	25	539	197.8	84.9
Tele-Quebec	30	569	141.3	84.8
Radio Canada	33	587	197.8	83.8
V-Tele	34	593	141.3	74.8

* H_{Tx} is the height of the antenna relative to the bottom of tower.

a first ChEst for LBS cancellation and the 2nd ChEst to estimate the FWS channel for STL signal detection.

For WIDL-LDM, a more complicate receiver is needed which is plotted in Figure 15. An additional signal processing module is needed to first cancel the CL broadcast service signal. The CL signal cancellation does not pose a challenge, since the A-Tx and R-Tx transmit the same CL signal for SFN operation. The receiver simply performs the conventional successive signal cancellation, treating the combined FWS and LBS as a single 2-layer LDM signal.

V. A CASE STUDY IN OTTAWA

A measurement campaign was carried out in Ottawa area to evaluate the feasibility of implementing WIDL in an ATSC 3.0 SFN using an existing DTV tower as A-Tx. The DTV tower is a 229-meter tower located on top of mountain Camp Fortune, Chelsea, Quebec, with a sea level of 360 meters. Six DTV channels are evaluated, for which the parameters are listed in TABLE IV.

It is shown in Figure 17 that for all measurement points, the received FWS signal power is higher than -60 dBm.

Next, the loopback power levels for different TV stations are measured at the bottom of the transmission tower. The loopback power levels could be scaled to calculate the actual loopback power level as,

$$P_{LBS}(d_1) = P_{LBS}(d_0) + 20 \log_{10} \frac{d_0}{d_1} \quad (11)$$

where d_0 is the height of the transmission antenna, d_1 is the distance of the RS-Rx antenna to the R-Tx transmission antenna, assuming d_1 is at least 10 meters.

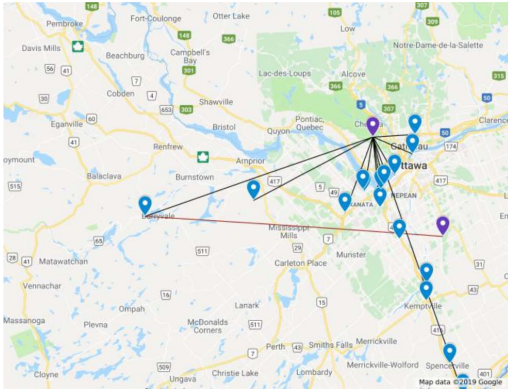


Fig. 16. Measurement campaign map in Ottawa.

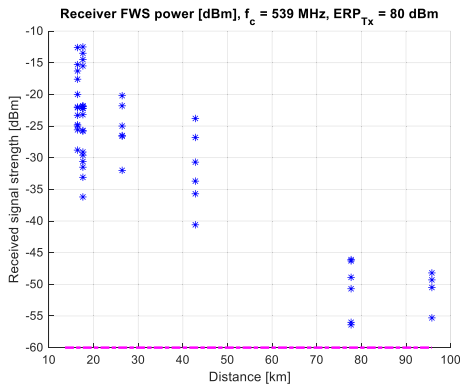


Fig. 17. Received FWS signal power.

Based on the measurement of the received signal power and the LBS power estimation from (11), the power ratio of LBS/FWS for different channels at different locations are calculated and plotted in Figure 18, for an R-Tx emission power of 70 dBm and a Tx-Rx antenna distance of 30 m.

It is shown that, even for a distance close to 100 km, the LBS over FWS power ratio is always less than 30 dB. From Figure 12, it is clearly shown that a low-complexity LBS cancellation module could achieve a residual LBS signal (after cancellation) 30 dB lower than the FWS signal.

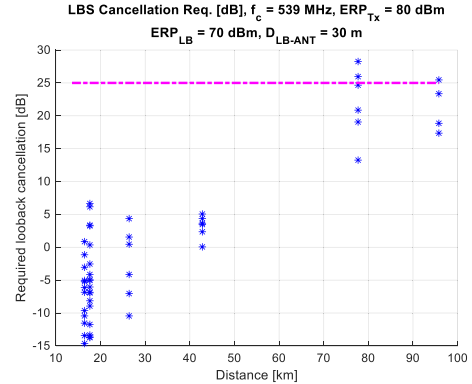
This Case Study shows that the WIDL could be realized at all testing points, even those with elevations lower than 10 meters. The actual implementation with a high tower should have much better performance.

VI. FUTURE EVOLUTIONS

There are many possible extensions to the proposed WIDL technology, to support more application scenarios and to achieve higher spectral efficiency.

A. Multi-Hop Distribution and Mesh Network

The concept of WIDL could be extended to deliver the distribution data over multiple hops, which could eventually

Fig. 18. P_{LBS}/P_{FWS} power ratio.

lead to a mesh distribution network in an SFN as shown in Figure 19(a). The A-Tx delivers the STL data to the two closest R-Tx in one hop, where the 1st hop R-Tx's then delivers the STL data to R-Tx's farther away. In this case, the longest multi-hop distribution link consists of three hops. To accomplish SFN transmission from the A-Tx and all the R-Tx's, the STL data delivered from the A-Tx needs to have a time advance of 3T over the service data emitted in the same ATSC 3.0 signal; in the signals emitted from the 1st hop R-Tx's, the STL data has a time advance of 2T; and so on for the R-Tx's in the following hops. The R-Tx's in the last hop delivers only service data.

In this mesh network, one R-Tx has multiple paths to obtain the STL data. A network management entity (NME) could help to organize the propagation path of the multi-hop distribution link for each R-Tx. In the case of one R-Tx fails, as shown in Figure 19(b), the NME could re-route the STL link for the subsequent R-Tx's original receiving distribution data from the failed R-Tx. Therefore, this multi-hop structure provides more failure tolerance in the entire SFN.

B. Three-Layer LDM

A third layer could be introduced to deliver the STL data for the CL mobile service only. This could reduce the capacity loss of the EL fixed services. Two configurations of using 3-layer LDM to deliver in-band STL data are plotted in Figure 20, where Figure 20(a) shows an LDM-STL solution and Figure 20(b) shows the STL-TDM solution.

The required STL time percentage and the transmission throughput of the mobile/fixed service and STL link are calculated and summarized in TABLE V. Comparing to the capacities for 2-layer solutions in TABLE I, one can see some saving in the fixed service capacity by using the 3-layer WIDL solutions.

C. Application of VVC

The next-generation video coding after HEVC (H.265) is called Versatile Video Coding (VVC) and will be standardized in 2020. The target of VVC is to achieve another 50% gain

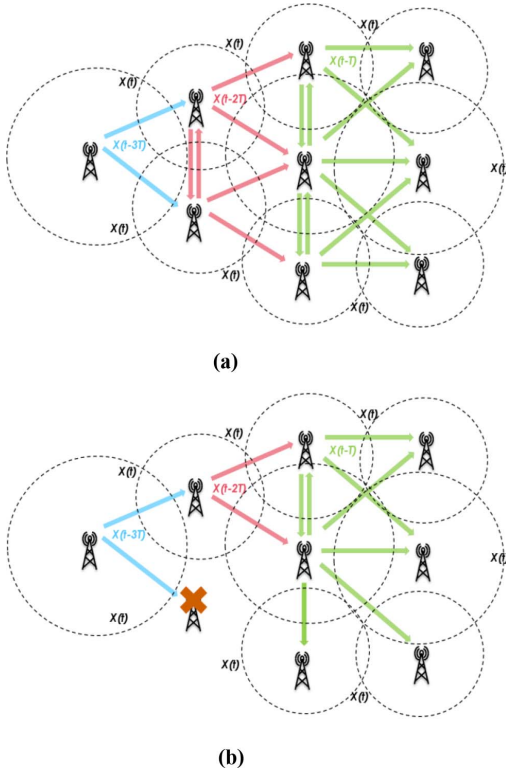


Fig. 19. Multi-hop WIDL SFN network; (a) SFN mesh network; (b) SFN mesh network with Tx failure and re-route.

in compression ratio. Therefore, using VVC could reduce the required data rate by almost half for the same broadcast service video quality.

VVC offers a solution to further reduce the amount of radio resource to deliver the in-band distribution data. Without changing the video decoder at the consumer receivers, the video services could be encoded using VVC and distributed from the BGW to the remote broadcast transmitters. This would reduce the amount of required radio resource for STL transmission by almost half and leave more capacity for service delivery.

In order to use VVC to achieve higher spectral efficiency for STL delivery, a VVC to HEVC transcoder needs to be implemented at the R-Tx's. This would guarantee backward compatibility, i.e., no impact to consumer receivers.

VII. WIDL VERSUS ON-CHANNEL REPEATER

On-channel repeater (OCR) is an existing cost-effective solution to provide terrestrial TV coverage area extension and to fill coverage holes [26]–[28]. In this section, the proposed WIDL technology is compared to existing OCR solutions to demonstrate its performance advantages and additional capabilities in the next generation DTV system.

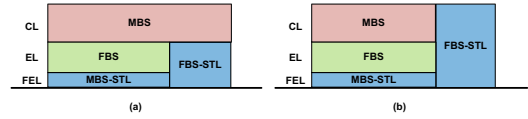


Fig. 20. WIDL signal model for both mobile and fixed services distribution only: (a) TDM; (b) LDM.

TABLE V
EXAMPLES OF WIDL SCENARIOS WITH TDM AND LDM

		WIDL (%)	MBS [Mbps]	FBS [Mbps]	STL [Mbps]
STL-SISO	TDM	33%	2.6	10.7	13.4
	LDM	41%	4.0	9.5	13.5
STL-MIMO	TDM	20%	3.2	12.8	16.0
	LDM	24%	4.0	12.1	16.1
STL-MIMO 3-Layer	TDM	17%	3.3	13.3	13.3/3.3
	LDM	20%	4.0	12.9	12.9/4.0
No WIDL		0%	4.0	16.0	0

A. On-Channel Repeater

An OCR usually receives a broadcast signal from a TV transmitter, amplifies it, and re-transmits the signal on the same TV channel. Since the power amplifier usually introduces additional noise into the received signal, the OCR output signal always suffers a lower SNR as comparing to the input signal. This makes it difficult to use OCR to cover large areas.

A significant challenge for OCR is the impact of the feedback signal from the re-transmission antenna to the receive antenna. Because the feedback signal is usually much stronger than the received signal, it could cause system oscillations and disable the operation of the OCR [27].

Therefore, reducing the feedback signal power is critical for proper operation of an OCR. Existing solutions in the literature include physical isolation methods and echo cancellation (EC). Physical isolation methods include antenna placement and antenna directivity, which has been shown to achieve a feedback signal attenuation of 30-50 dB. Further feedback signal isolation could be achieved by EC.

Two commonly used EC approaches are the decision-feedback based EC (DF-EC) and FIR-filter-based EC (FIR-EC). It is shown in [28] that using DF-EC could achieve 30 dB cancellation of the feedback signal. However, the DF-EC is designed for a single-carrier transmission such as ATSC 1.0, and cannot be directly applied to the OFDM-based ATSC 3.0 system [12]. The FIR-EC methods, although they are applicable to ATSC 3.0, could suffer significant noise enhancement due to the linear equalization process. This requires the input signal at the OCR to have very high SNR to achieve high-quality re-transmission.

All these limitations suggest that OCR should be used for isolated small areas, with also limitations on service qualities.

B. Wireless in-Band Distribution Link

In the proposed WIDL, an R-Tx decodes the received STL signal emitted from the A-Tx and re-transmits a clean ATSC

TABLE VI
WIDL vs OCR

WIDL	OCR
- Output clean signal	- Output SNR lower than input SNR
- Does not require high-SNR input	- Requires high SNR input
- Always provides stable operation	- Even with EC, stable operation is not guaranteed
- Could support medium to high output power, i.e., medium to large areas	- Limited output power, i.e., small areas
- Easy to implement multi-hop	- Difficult to support multi-hop links
- Supports STL/backhaul of local services and non-broadcast services, e.g., IoT, connected car	- No support for distribution of different services
- Some service capacity loss	- No service capacity loss

3.0 signal. The output signal quality is much better than that from an OCR.

Similar to OCR, a practical realization of R-Tx also faces the challenge of loopback signal from the transmit antenna to the RS-Rx receive antenna. However, because high-performance signal cancellation could be realized by digital signal processing, the loopback signal isolation requirement is more relaxed as comparing to the OCR solutions.

Therefore, WIDL could be used to deploy R-Tx for large coverage areas.

Furthermore, in WIDL-based systems, the STL link could be used to deliver distribution data for other types of services, in addition to the SFN broadcast services. In future DTV networks, different R-Tx could deliver location-based services to receivers within their own coverage area. These could include local news/commercials, IoT services, connected vehicles, etc., which cannot be realized by OCR.

C. OCR vs WIDL

In TABLE VI, the benefits and additional capabilities of the proposed WIDL technology over OCR are summarized.

It needs to be pointed out that, while OCR lacks many capabilities of WIDL, it serves as a cost-efficient solution to provide broadcast service coverage extensions over areas with favorable conditions. In addition, OCR can be combined with WIDL as the last hop solution in a multi-hop SFN scenario.

The advantages of WIDL are achieved at the cost of more signal processing in the RS-Rx for loopback signal cancellation and an RF tuner with high dynamic range. This added cost is insignificant considering the RS-Rx receiver being a professional equipment.

In addition, using WIDL results in less radio resources for service delivery. However, with the much higher transmission capacity offered by ATSC 3.0, there is plenty of capacity

for both STL and services using one RF channel. This will become even less an issue when the next generation video coding (VVC) is adopted.

VIII. CONCLUSION

A wireless in-band distribution (WIDL) technology is proposed to enable fast and cost-efficient deployment of the next generation ATSC 3.0 single-frequency-network. In WIDL, the service distribution data is transmitted from an existing high transmission tower to the newly deployed SFN transmitters, sharing the same TV band with the broadcast services. To achieve higher spectral efficiency, LDM technology is proposed to multiplex the distribution data with the service data in the same ATSC 3.0 signal. Different signal configurations to realize the WIDL are presented with different capacity vs complexity tradeoffs. It is shown that the significantly higher capacity of ATSC 3.0 allows the transmission of distribution data over the same TV channel with the service data and still provides both mobile and fixed 4k-UHD broadcast services, i.e., more services than the existing ATSC 1.0 system at much higher qualities. A detailed study on the implementation of WIDL at remote SFN sites shows that a practical WIDL receiver could be designed using conventional signal isolation approaches and low complexity signal processing algorithms, i.e., no new algorithms need to be designed. A case study in Ottawa area is also reported to demonstrate the feasibility of the proposed WIDL technology.

The proposed WIDL technology is essentially a wireless backhaul solution which could play a key role to enable the success of the ATSC 3.0 system to deliver location-based services, IoT, connected vehicles, and others.

REFERENCES

- [1] *NGMN 5G White Paper*, NGMN Alliance, Frankfurt, Germany, Feb. 2015. Accessed: Nov. 25, 2017. [Online]. Available: https://www.ngmn.org/fileadmin/ngmn/content/downloads/Technical/2015/NGMN_5G_White_Paper_V1_0.pdf
- [2] L. Fay, L. Michael, D. Gómez-Barquero, N. Ammar, and M. W. Caldwell, "An overview of the ATSC 3.0 physical layer specification," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 159–171, Mar. 2016.
- [3] A. Mattsson, "Single frequency networks in DTV," *IEEE Trans. Broadcast.*, vol. 51, no. 4, pp. 413–422, Dec. 2005.
- [4] U. Meabe, X. Gil, C. Li, M. Velez, and P. Angueira, "On the coverage and cost of HPHT versus LPLT networks for rooftop, portable, and mobile broadcast services delivery," *IEEE Trans. Broadcast.*, vol. 61, no. 2, pp. 133–141, Jun. 2015.
- [5] L. Zhang *et al.*, "Layered-division-multiplexing: Theory and practice," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 216–232, Mar. 2016.
- [6] O. Bulacki, "On backhauling of relay enhanced network sin LTE-advanced," Licentiate Seminar, Dept. Commun. Netw., Aalto Univ., Espoo, Finland, 2010.
- [7] "Further advancements for E-UTRA, physical layer aspects, V1.5.1," 3GPP, Sophia Antipolis, France, Rep. TR-36.814, Dec. 2009.
- [8] C. Hoymann, W. Chen, J. Montojo, A. Golitschek, C. Koutsimanis, and X. Shen, "Relaying operation in 3GPP LTE: Challenges and solutions," *IEEE Commu. Mag.*, vol. 50, no. 2, pp. 156–162, Feb. 2012.
- [9] C. Zarbouti, G. Tsoulos, and G. Athanasiadou, "4G multicell systems with in-band full duplex relays: Using beamforming to lower self-interference and/or transmitted powers," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC'2015)*, Glasgow, U.K., May 2015, pp. 1–6.
- [10] P. P. Bergmans and T. M. Cover, "Cooperative broadcasting," *IEEE Trans. Inform. Theory*, vol. 20, no. 3, pp. 317–324, May 1974.
- [11] L. Zhang *et al.*, "Using layered-division-multiplexing for in-band backhaul for ATSC 3.0 SFN and gapfillers," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Valencia, Spain, Jun. 2018, pp. 1–6.

- [12] L. Zhang *et al.*, "ATSC 3.0 in-band backhaul for SFN using LDM with full backward compatibility," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jeju-do, South Korea, Jun. 2019, pp. 1–6.
- [13] L. Zhang *et al.*, "Using non-orthogonal multiplexing for in-band full-duplex backhaul for 5G broadcasting," in *Proc. IEEE 5G World Forum (5GWF)*, Silicon Valley, CA, USA, Jul. 2018, pp. 1–6.
- [14] K.-J. Kim *et al.*, "Low-density parity-check codes for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 189–196, Mar. 2016.
- [15] N. Loghin, J. Zöllner, B. Mouhouche, D. Anzorregui, J. Kim, and S. Park, "Non-uniform constellations for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 197–203, Mar. 2016.
- [16] D. Gómez-Barquero *et al.*, "MIMO for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 298–305, Mar. 2016.
- [17] L. Zhang *et al.*, "Layered-division-multiplexing for high spectrum efficiency and service flexibility in next generation ATSC 3.0 broadcast system," *IEEE Wireless Commun.*, vol. 26, no. 2, pp. 116–123, Apr. 2019.
- [18] D. Kim, H. Li, and D. Hong, "A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers," *IEEE Commun. Surv. Tuts.*, vol. 17, no. 4, pp. 2017–2046, 4th Quart. 2015.
- [19] *Technical Report: Informe Pruebas Aislamiento En KONTRASTA, ITELAZPI*, Zamudio, Spain, Dec. 2012.
- [20] *ATSC Recommended Practice: Design of Multiple Transmitter Networks*, document A/111:2009, Adv. TV Syst. Committee, Washington, DC, USA, Sep. 2009.
- [21] J.-J. Van De Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Borjesson, "On channel estimation in OFDM systems," in *Proc. 45th Veh. Technol. Conf. (VTC'95)*, vol. 2, Chicago, IL, USA, Jul. 1995, pp. 715–719.
- [22] O. Edfors, M. Sandell, J.-J. Van De Beek, S. K. Wilson, and P. O. Borjesson, "OFDM channel estimation by singular value decomposition," *IEEE Trans. Commun.*, vol. 46, no. 7, pp. 931–939, Jul. 1998.
- [23] L. Zhang, Z. Hong, and L. Thibault, "Improved DFT-based channel estimation for OFDM systems with null subcarriers," in *Proc. Veh. Technol. Conf. (VTC)*, Anchorage, AK, USA, Sep. 2009, pp. 1–5.
- [24] Commission of European Communities, Directorate General, Telecommunications, and Information Industries and Innovation, *Digital Land Mobile Radio Communications. COST 207 Report*. Luxembourg, Europe: OPOCE, 1989.
- [25] S. W. Kim, Y. T. Lee, S. I. Park, H. M. Eum, J. H. Seo, and H. M. Kim, "Equalization digital on-channel repeater in the single frequency network," *IEEE Trans. Broadcast.*, vol. 52, no. 2, pp. 137–146, Jun. 2006.
- [26] M. Wang, "Dynamic gain management for on-channel repeaters," *IEEE Trans. Broadcast.*, vol. 59, no. 4, pp. 685–692, Dec. 2013.
- [27] K. M. Nasr, J. P. Cosmas, M. Bard, and J. Gledhill, "Performance of an echo canceller and channel estimator for on-channel repeaters in DVB-T/H networks," *IEEE Trans. Broadcast.*, vol. 53, no. 3, pp. 609–618, Sep. 2007.
- [28] S. W. Kim, Y. T. Lee, S. I. Park, H. M. Eum, J. H. Seo, and H. M. Kim, "Equalization digital on-channel repeater in the single frequency networks," *IEEE Trans. Broadcast.*, vol. 52, no. 2, pp. 137–146, Jun. 2006.



Liang Zhang (Senior Member, IEEE) received the bachelor's degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei, China, in 1996, and the M.S. and Ph.D. degrees from the Department of Electrical and Computer Engineering, University of Ottawa, Ottawa, Canada, in 1998 and 2002, respectively. He is a Senior Research Scientist with the Communications Research Centre Canada, Ottawa. He has been deeply involved in the ATSC 3.0 standardization activities on developing the layered-division-multiplexing technology, mixed fixed and mobile broadcast service delivery, mobile service detection, co-channel interference mitigation, integrated access and backhaul. He is currently working on technologies for the convergence of future TV broadcast and 5G broadband systems. He has more than 70 peer-reviewed journal and conference publications and received multiple Best Paper Awards from IEEE, IBC, and NAB for his work on the next generation ATSC 3.0 and the 5G broadcasting systems. He is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, a IEEE BTS Distinguished Lecturer, and an Elected Member of the IEEE BTS Administrative Committee.

oping the layered-division-multiplexing technology, mixed fixed and mobile broadcast service delivery, mobile service detection, co-channel interference mitigation, integrated access and backhaul. He is currently working on technologies for the convergence of future TV broadcast and 5G broadband systems. He has more than 70 peer-reviewed journal and conference publications and received multiple Best Paper Awards from IEEE, IBC, and NAB for his work on the next generation ATSC 3.0 and the 5G broadcasting systems. He is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, a IEEE BTS Distinguished Lecturer, and an Elected Member of the IEEE BTS Administrative Committee.



Wei Li (Member, IEEE) received the B.E. degree in electrical engineering from Shandong University in 1985, the M.S. degree in electrical engineering from the University of Science and Technology of China, in 1988, and the Ph.D. degree in electrical engineering from the Institut National des Sciences Appliquées de Rennes, France, in 1996. In 2001, he joined Communications Research Centre Canada (CRC), where his major focus is broadband multimedia systems and digital television broadcasting. He is currently a Research Scientist with CRC.

He served as the Session Chair for the IEEE International Symposium on Broadband Multimedia Systems and Broadcasting in 2006, 2007, 2015, and 2016, and a TPC Chair in 2016. He was the Managing Editor of the IEEE TRANSACTIONS ON BROADCASTING Special Issue on IPTV in Broadcasting Applications in 2009. He also served as a reviewer for several renowned international journals and conferences in the area of broadcasting, multimedia communication, and multimedia processing. He was the BTS IPTV representative at the ITU-T and the Co-Chair of Enhanced TV Planning Team at ATSC. He is an Associate Editor for the IEEE TRANSACTIONS ON BROADCASTING and IEEE ACCESS.



Yiyun Wu (Fellow, IEEE) received the M.Eng. and Ph.D. degrees in electrical engineering from Carleton University, Ottawa, Canada, in 1986 and 1990, respectively. He is a Principal Research Scientist of the Communications Research Centre Canada. He has more than 400 publications and received many technical awards for his contribution to the research and development of digital broadcasting and broadband multimedia communications. His research interests include broadband multimedia communications, digital broadcasting, and communication systems engineering. He is a Fellow of the Canadian Academy of Engineering, an Adjunct Professor of Carleton University, and Western University in Canada. He is a Distinguished Lecturer of the IEEE Broadcast Technology Society, and a member of the ATSC Board of Directors, representing IEEE. He was appointed as a Member of the Order of Canada in 2018.



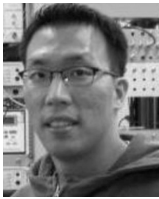
Sébastien Laffèche received the B.A.Sc. degree in electrical engineering from the University of Ottawa in 1999 and upon graduation has joined the Communications Research Centre Canada. For over 15 years, he has been working in the evaluation and testing of advanced digital broadcasting systems. His experience includes single frequency network, mobile digital television, coverage simulation, and new broadcasting services. He expanded his knowledge by conducting research on 3GPP LTE. His research interests include digital broadcasting, spectrum sharing, LTE communications, and quality of service.



Zhihong Hong received the B.S. degree in electrical engineering from Tsinghua University, Beijing, China, in 1994, and the M.S. and Ph.D. degrees in electrical engineering from North Carolina State University, Raleigh, in 1998 and 2002, respectively. From 1999 to 2002, he was a Research Assistant with the Center for Advanced Computing and Communication, North Carolina State University. From 2002 to 2003, he was with the University of Wisconsin at Madison, as a Postdoctoral Research Associate. Since August 2003, he has been a Research Scientist with Communications Research Centre Canada. His research interests include advanced coding and modulation in wireless communications.



Sung-Ik Park (Senior Member, IEEE) received the B.S.E.E. degree from Hanyang University, Seoul, South Korea, in 2000, the M.S.E.E. degree from POSTECH, Pohang, South Korea, in 2002, and the Ph.D. degree from Chungnam National University, Daejeon, South Korea, in 2011. Since 2002, he has been with the Broadcasting System Research Group, Electronics and Telecommunications Research Institute (ETRI), where he is the Project Leader and the Principal Member of Research Staff. He has over 200 peer-reviewed journal and conference publications, and multiple best paper and contribution awards for his work on broadcasting technologies. His research interests are in the area of error correction codes and digital communications, in particular, signal processing for digital television. He currently serves as an Associate Editor for the IEEE TRANSACTIONS ON BROADCASTING and *ETRI Journal*, and a Distinguished Lecturer of IEEE Broadcasting Technology Society.



Jae-young Lee (Senior Member, IEEE) received the B.S. degree (High Hons.) in electrical and computer engineering from Rutgers University in 2001, the M.S. degree in electrical and computer engineering from the University of Wisconsin at Madison in 2003, and the Ph.D. degree in engineering science from Simon Fraser University in 2013. He joined Electronics and Telecommunications Research Institute in 2003, where he is currently a Principal Research Associate with Broadcasting Systems Research Group. His research interests are

in the areas of digital signal processing for various applications, including digital broadcasting, telecommunications, and human-computer interaction systems.



Heung Mook Kim (Member, IEEE) received the B.S. and M.S. degrees in electronics and electrical engineering from POSTECH, Pohang, South Korea, in 1993 and 1995, respectively, and the Ph.D. degree from KAIST, Daejeon, South Korea, in 2013. He was with POSCO Technology Research Laboratory, Pohang, from 1995 to 2001, and Maxwave, Inc., Daejeon, from 2002 to 2003. Since 2004, he has been with Electronics and Telecommunications Research Institute, Daejeon, where he is the Managing Director of Media

Transmission Technology Research Group. He is currently a Vice-Chair of Broadcasting Technical Committee (TC8) of TTA, South Korea, and Managing Committee of Future Broadcast Media Standard Forum, South Korea, and the Chair of Physical Layer Group of FOBTV Technical Committee. His research interests are in the areas of digital and RF signal processing and multi-platform contents delivery for digital broadcasting and broadband multimedia communications.



Namho Hur (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from the Pohang University of Science and Technology, Pohang, South Korea, in 1992, 1994, and 2000, respectively. He is currently with the Broadcasting and Media Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, South Korea, where he is the Project Leader of "Development of Transmission Technology for Ultra High Quality UHD." He was the Chair of Future of Broadcast

Television Initiative Management Committee from April 2018 to April 2019. His research interest includes realistic digital broadcasting systems.



Eneko Iradier (Graduate Student Member, IEEE) received the B.Sc. and M.Sc. degrees in telecommunications engineering from the University of the Basque Country (UPV/EHU) in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree. Since 2015, he has been part of the TSR Research Group, UPV/EHU. He was with the Communications Systems Group of IK4-Ikerlan as a Researcher from 2017 to 2018. During his doctoral studies, he did an internship with Communications Research Centre Canada, Ottawa.

His current research interests include the design and development of new technologies for the physical layer of communication systems and broadcasting in 5G environments.



Pablo Angueira (Senior Member, IEEE), received the M.S. and Ph.D. degrees in telecommunication engineering from the University of the Basque Country, Spain, in 1997 and 2002, respectively. He joined the Communications Engineering Department, University of the Basque Country in 1998, where he is currently a Full Professor. He is part of the staff of the Signal Processing and Radiocommunication Lab, where he has been involved in research on digital broadcasting (DVB-T, DRM, T-DAB, DVB-T2, DVB-NGH, and ATSC 3.0) for more than 20 years. He has coauthored an extensive list of papers in international peer-reviewed journals, and a large number of conference presentations in digital broadcasting. He has also coauthored several contributions to the ITU-R working groups WP6 and WP3. His main research interests are network planning and spectrum management applied to digital terrestrial broadcast technologies. He is currently involved in research activities related to broadcasting in a 5G environment. He is an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING, a member of the IEEE BMSB International Steering Committee, and a Distinguished Lecturer of the IEEE Broadcast Technology Society. He serves on the Administrative Committee for the IEEE Broadcast Technology Society.



Jon Montalban (Member, IEEE) received the M.S. and Ph.D. degrees in telecommunications engineering from the University of the Basque Country, Spain, in 2009 and 2014, respectively. He is part of the Radiocommunications and Signal Processing Research Group, University of the Basque Country, where he is an Assistant Professor involved in several research projects. He has held visiting research appointments with the Communication Research Centre, Canada, and Dublin City University, Ireland. His current research interests are in the area of

wireless communications and signal processing for reliable industrial communications. He is the co-recipient of several best paper awards, including the Scott Helt Memorial Award to Recognize the Best Paper Published in the IEEE TRANSACTIONS ON BROADCASTING in 2019. He has served as a reviewer for several renowned international journals and conferences in the area of wireless communications. He is currently serves as an Associate Editor for IEEE ACCESS.

3.3.3 Aldizkari-artikula (A9)

Azpiatal honek 1. kontribuzioari buruzko konferentzia-artikulu bat aurkezten du . Artikuluaren erreferentzia osoa ondorengoa da:

- W. Li, L. Zhang, Y. Wu, Z. Hong, S. Lafleche, S-I. Park, S. Kwon, S. Ahn, N. Hur, E. Iradier, I. Bilbao, J. Montalban and P. Angueira, "Integrated Inter-Tower Wireless Communications Network for Terrestrial Broadcasting and Multicasting Systems," IEEE Transactions on Broadcasting aldizkarian argitaratzeko onartua.

Hona hemen artikulua honen kalitate-adierazle adierazgarrienak:

- Argitalpen mota: IEEEExplore eta JCR-n indexatutako aldizkaria
- Saila: Ingeniaritza elektrikoa eta elektronikoa
- Sailkapena: 69/266 (Q2) 2019ko JCRan oinarrituta
- Inpaktu-faktorea (JCR): 3,419

Integrated Inter-Tower Wireless Communications Network for Terrestrial Broadcasting and Multicasting Systems

Wei Li, *Member IEEE*, Liang Zhang, *Senior Member, IEEE*, Yiyao Wu, *Fellow, IEEE*, Zhihong Hong, Sébastien Lafleche, Sung-Ik Park, *Senior Member, IEEE*, Sunhyoung Kwon, Sungjun Ahn, *Member*, Namho Hur, *Member, IEEE*, Eneko Iradier, *Graduate Student Member, IEEE*, Iñigo Bilbao, *Graduate Student Member, IEEE*, Jon Montalban, *Senior Member, IEEE*, and Pablo Angueira, *Senior Member, IEEE*

Abstract—This paper describes systems, devices, and methods to implement a bi-directional integrated inter-tower wireless communications network (IITWCN). The described technology can be implemented in combination with the Broadcast Core Network (BCN) in next generation broadcast eco-system and, therefore, support new business cases for broadcast operators such as the delivery of flexible datacasting services or support broadcast or point-to-point internet services. The introduced bi-directional inter-tower communications network (ITCN) extends the previous unidirectional in-band distribution links (IDL) and adopts the on-channel repeater (OCR) as a simplified backhaul solution in single frequency networks (SFN). The concept of the coordinated ITCN is also presented, aiming at future broadcast internet services. The ITCN provides a scalable and configurable network solution embedded in a broadcast system, which becomes independent from any non-broadcasting telecommunication infrastructure. The described technology partially relies on the infrastructure of the underlying broadcast/multicast network, using the allocated service channels without requiring additional frequency bands or a separate frequency band. The bi-directional inter-transmitter communication links are therefore referred to as integrated transmission links and the corresponding network as an integrated network.

Index Terms—LDM, SFN, STL, In-band Backhaul, Wireless Inter-Tower Communications Network, OCR, Full Duplex Transmission, Broadband and Broadcasting Convergence, Broadcast Core Network

I. INTRODUCTION

THE next generation digital TV (NextGen TV) broadcasting system (ATSC 3.0) is being deployed in North America. To provide robust mobile services to portable and handheld

devices, advanced transmission technologies such as layered-division multiplexing (LDM) [1], low-density-parity-check (LDPC) coding, non-uniform constellation (NUC) modulation, up to 32k FFT OFDM and MIMO, are adopted in ATSC 3.0 [2].

LDM is a power-based multi-layer signal multiplexing technology that achieves higher cumulative transmission capacity when delivering multiple services with different quality requirements [1] [3]-[11]. In a typical application scenario for a two-layer LDM, the first signal layer (L1 or Core Layer in ATSC 3.0 [12]-[14]) is configured with stronger power to deliver robust signals, targeting mobile, handheld, and indoor receivers. The second layer (L2 or Enhanced Layer in ATSC 3.0 [12]) is configured with lower power to deliver high-throughput signals. The high-throughput of the L2 signal is achieved by using fixed receivers with rooftop or other powerful high-gain antennas, which can provide high signal-to-noise ratio (SNR) reception. The signal model of a two-layer ATSC 3.0 system is shown in Fig. 1. A typical application scenario is to simultaneously deliver time and frequency synchronized L1 and L2 signals super-imposed within the same frequency band. At the receiver, L1 signal is decoded using a normal single layer receiver, considering L2 as an interference. L2 signal is detected using successive signal cancellation (SSC), which decodes, re-encodes the L1 signal, and cancels it from the received LDM signal. After the SSC, the L2 signal detection follows the conventional signal detection process.

Single frequency network (SFN) [15] has been considered as an effective broadcast network deployment solution since it provides better spectrum efficiency, less power consumption, higher coverage reliability, and much reduced adjacent-cell

This work was supported by Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.2017-0-00081, Development of Transmission Technology for Ultra High Quality UHD), and in part by the Basque Government (the grant IT1234-19 and the PREDOC grant program PRE_2020_2_0105) and by the Spanish Government (project PHANTOM under the grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE)). (Corresponding author: Wei Li).

W. Li, L. Zhang, Y. Wu, Z. Hong, and S. Lafleche are with the Communications Research Centre Canada, Ottawa, ON K2H 8S2, Canada (e-

mail: wei.li@canada.ca; liang.zhang@canada.ca; yiyao.wu@canada.ca; zhihong.hong@canada.ca; sebastien.lafleche@canada.ca).

S.-I. Park, S. Kwon, S. Ahn, and N. Hur are with the Broadcasting System Research Department, Electronics and Telecommunications Research Institute, Daejeon 305-700, South Korea (e-mail: psi76@etri.re.kr; shkwon@etri.re.kr; sjahn@etri.re.kr; namho@etri.re.kr).

E. Iradier I. Bilbao, J. Montalban and P. Angueira are with the Department of Communications Engineering, University of Basque Country, 48013 Bilbao, Spain (e-mail: eneko.iradier@ehu.eus; inigo.bilbao@ehu.eus; jon.montalban@ehu.eus; pablo.angueria@ehu.eus).

interference. Varied ranges of operation modes in ATSC 3.0 are defined with different cyclic prefix (CP) lengths, allowing flexible SFN deployments, to offer broadcast services with various quality requirements over explicit terrestrial areas. Instead of high tower high power (HTHP) transmitter deployment, the SFN provides the low tower low power (LTLP) solution, making the most of the service coverage and quality [16]. A studio-to-transmitter link (STL) connection is in need for each new SFN transmitter to transfer data from the broadcast gateway (BG) [17]. The number of required STL connections will grow proportionally as more SFN transmitters are being deployed. The current STL solutions relying on fiber links or dedicated microwave links suffer from both poor accessibility and high infrastructure and operation costs. New STL solutions that can offer both low installation and operation costs are required.

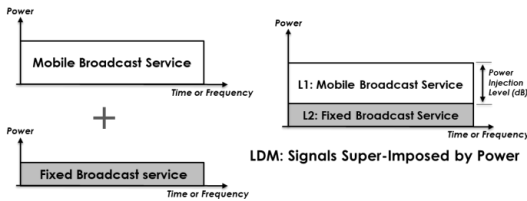


Fig. 1. A diagram illustrating a signal model of a 2-layer LDM system

An effective alternative using in-band backhaul (wireless in-band distribution link (IDL) technology) has been proposed in [18] [19]. It uses LDM to transmit the STL data via wireless links from the BG to the SFN transmitters within the same spectrum as the broadcast services. IDL guarantees full backward compatible ATSC 3.0 backhaul for SFN operation. Moreover, this solution is a complete in-band approach that provides backhaul for both robust mobile and high-data-rate fixed services. In addition, it has no impact on existing services for consumer TV receivers and it is a spectrum reuse technology that makes better use of the spectrum. The cost of applying IDL as backhaul in SFN is the potential partial occupancy of the transmitting spectrum, as well as a series of challenges such as loopback signal cancellation/isolation, transmitter timing control, etc.

Continuous efforts are carrying out on new solutions offering low installation and low operation costs for SFN distribution links, as well as more controllable, scalable, and cost-effective STL technologies. In Section II, on-channel repeaters (OCR) are proposed to be used within ATSC 3.0 SFN, which provide simplified low cost solutions. In Section III, the bi-directional IDL solution is proposed, which is named bi-directional wireless Inter-Tower Communications Network (ITCN). The ITCN provides full duplex transmission among SFN transmitters, aiming at enriched data services including IoT, emergency warning, connected car, and other localized data services. In Section IV, the coordinated ITCN concept is introduced, which applies for multiple operators sharing the same SFN or multiple SFNs coordination. The ITCN node at a broadcast transmitter site is also described in this section.

Integrated Inter-Tower Wireless Communications Network (IITWCN) indicates a large-scale wireless IP-network that inter-connects multiple SFN/ITCNs and Multi-Frequency Networks (MFN). In the last section, Section V, conclusions and discussions are presented.

II. USING OCR IN ATSC 3.0 SFN

OCRs have been used in terrestrial broadcasting systems [20] to provide additional coverage or to fill coverage holes. OCRs are classified into analog types, which include radio frequency (RF) and intermediate frequency (IF) processing OCRs, and digital types, which include OCRs with feedback interference canceler (FIC) and OCRs with equalizer. An OCR may also combine analog and digital signal processing.

An OCR is a low-cost implementation of SFN, where no inter-tower distribution link is required. Fig. 2 shows functional blocks of a digital OCR example with an equalizer [20] configured for inter-tower communications (ITC) signal injection, e.g. at an added LDM layer. An OCR, in its simplest form, may include a receiving antenna, a band pass filter, low noise amplifier(s), and a power amplifier connected to the transmitting antenna. It is also possible to down-convert the input signal to IF. The same local oscillator can be used to up-convert the IF to maintain the synchronization between the transmitted and received signals. An optional module for down converting the signal to baseband gives the possibility of making error corrections before retransmission.

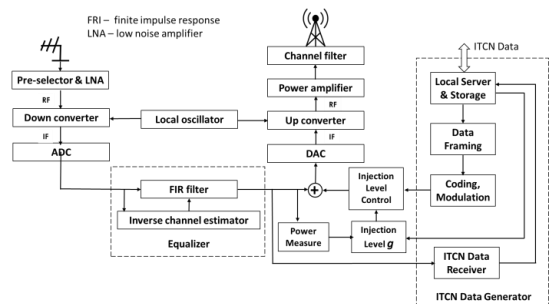


Fig. 2. A functional block diagram of an OCR with an ITCN signal injection.

In comparison to in-band backhaul solutions for a relay transmitter station (TS), the OCR has the advantage of simplicity and spectrum saving. It does not need to use service spectrum for backhaul signal delivery. An illustration of the OCR, rather than in-band backhaul link, is shown in Fig. 3. A targeted deployment is an SFN of broadcast services carried in the L1 and L2. In Fig. 3, the OCR transmitter Tx-C may be in a remote area or is located in a coverage hole of the SFN. Instead of deploying a dedicated fiber link or microwave link to carry the STL data, the broadcast L1 and L2 signals are picked up over-the-air from the other SFN transmitters, i.e., Tx-A or Tx-B, for processing and re-transmission by OCR. The operation of the OCR relay (Fig. 3) may be explained in detail as follows:

- The targeted SFN broadcast service to end users may be delivered in L1 and L2 from all transmitters: Tx-A, Tx-

B, and Tx-C.

- A directional high-gain antenna may be installed at a high location at the Tx-C, to achieve a good channel condition from Tx-A (or Tx-B), ideally a line of sight (LOS) channel.
- Since the receiving antenna of the OCR may be very close to the transmission antenna of Tx-C, sufficient signal isolation may be needed to prevent the Tx-C transmission signal from interfering with the signal detection process. If isolation is not high enough, it might also cause system instability;
- OCR may simply pick up the over-the-air signal and use signal processing in the analog [21] and/or digital domain [20] to eliminate the multipath distortion and loopback signal from the re-transmission antenna. The advantage of OCR is its simplicity since it does not need to decode the backhaul signal and generate the service signal.

The weak points may be: (1) since OCR cannot control the emission time, the signal processing delay needs to be relatively small, e.g., in tens of micro-second level, to reduce the multipath delay spread in the service area; (2) OCR may not be allowed to transmit very high power, e.g. under 500W, to prevent the system stability problem caused by loopback signal; (3) since there is no demodulation/decoding and remodulation/reencoding to clear up the signal, each OCR may cause some signal deterioration, which will accumulate in multi-hop OCR relay cases. The number of OCR relay stages may therefore be limited.

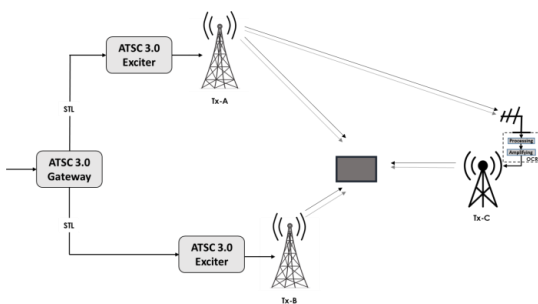


Fig. 3. A schematic diagram of an example ATC 3.0 Single Frequency Network with OCR as in-band relay.

An example scenario of ATSC 3.0 SFN with OCRs is illustrated in Fig. 4. This situation may happen when an SFN service area is not covered by the main transmitter Tx-A. Three OCRs receiving LDM L1 and L2 data from Tx-A form an SFN for a cost-effective solution.

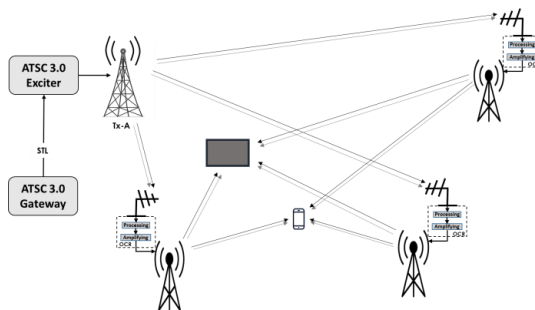


Fig. 4. A schematic diagram of an example ATC 3.0 SFN with three OCR relays.

III. BI-DIRECTIONAL INTER-TOWER WIRELESS COMMUNICATIONS NETWORK

The IDL technology [18] [19] provides a one-way in-band backhaul data transmission solution. In this section, it will be shown that sending the signal back in the same time frame is also possible. Remote SFN towers may be much higher than the 10-meter home reception antennas, so that there may be LOS paths among SFN towers, making it possible to implement a two-way inter-tower network. In particular, an in-band full-duplex transmission among towers can be implemented.

A. Two-Way Inter-Tower Communications Network

In Fig. 5, a simple ATSC 3.0 LDM based SFN with ITCN using bi-directional inter-tower communication (ITC) signals is illustrated. The ITCN shown may also support local datacasting. The operation of the in-band backhaul using two-layer LDM may be the same as explained in [18], or the backhaul may be provided via an STL link in some implementations. In the meantime, Tx-A can transmit ITC signals to Tx-B and vice versa, e.g. through LOS paths, which are multiplexed with conventional broadcast/multicast services (MS) signals, e.g. TV broadcast, and possibly in-band backhaul signals, using TDM, FDM and/or LDM. Each SFN tower can emit different ITCN data, transmitting different ITC signals on the same frequency band. Different types of services can be delivered embedded in ITC signals and can be received within each tower's broadcast coverage. These can include broadcast network cue and control data for network operation and monitoring, which are not intended for consumer services. ITCN data can also include consumer or professional service data, such as IoT, emergency warning, software download, connected car, and other localized data services or advertisement. The combination of TDM+LDM, or FDM+LDM, different modulation/coding, and reception conditions can provide tiered services for different robustness, data rates, and reception conditions.

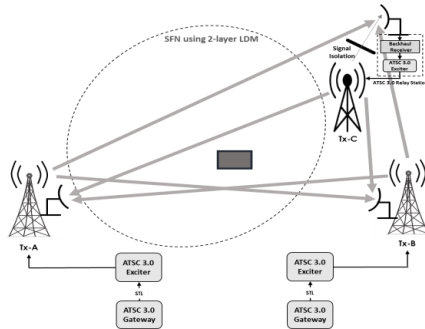


Fig. 5. A schematic diagram of ATSC 3.0 SFN with ITCN.

Different reception antennas might be used for over the air (OTA) ITCN signal reception to limit the co-channel interference from undesired transmission towers during the ITCN transmission. Some towers can operate as SFN with main transmitters, if desired. In some scenarios, an ITCN can also connect transmission towers that are not part of the SFN, but nearby towers transmitting on a different frequency. This scenario makes signal reception easier since there is no loopback signal cancellation needed like for SFN towers. The in-band backhaul and ITCN may be mutually independent. They can co-exist, or they can be implemented independently. In-band backhaul can be replaced with other communication methods, such as OCR. The ITCN is an embedded network in the broadcast infrastructure and can operate independently from any other telecommunications infrastructure, which makes it extremely robust.

Most of the datacasting content/information is non-real-time, which may be desirable to have a data server at each participating tower to store the datacasting content/information and broadcast out locally, e.g., as data-carousel. The timing and content can be controlled by an ITCN administrator via an ITCN server. This approach can also reduce the data rate requirement on the ITCN.

For the Tx-A to receive the ITCN data from Tx-B, since the receiving antenna may be very close to its broadcast transmission antenna, sufficient signal isolation may be needed to prevent the Tx-A transmission signal, also called the loopback signal, from interfering with the ITCN signal emitted from Tx-B [19].

Fig. 6 shows an example of two ATSC 3.0 LDM-based OCR SFN interconnected with ITCN. In this example, each OCR SFN (circled separately) is composed of three OCR relay stations, and the two SFNs are working generally independently, e.g., serving different geographical areas, and may be operating on different frequencies. All the towers in the Tx-A SFN are connected in star type of configuration [22]. The Tx-B SFN uses a ring topology. There are inter-SFN ITCN connections to link the two SFN networks, which could be between two main transmitters or between two OCRs. All main transmitters (i.e., Tx-A and Tx-B) and OCR-SFN transmitters can be connected via multi-hop transmission. The network topology is reconfigurable and scalable, if one tower fails the

data can be re-routed to reach all towers.

ITCN services using the same frequency band can be established among the towers in each OCR SFN. To limit the co-channel interference during the ITCN period, different reception antennas may be used for over the air ITCN signal reception from different adjacent towers. In this example, the ITCN transmission connections between Tx-A and Tx-B might be on different transmission frequencies. Tx-A and Tx-B may each combine an in-band transmission with out-of-band reception when communicating with each other.

Each transmitter site can also have a local server that may store data for control and local datacasting. All OCR transmitters can be replaced by SFN transmitters (non-OCR) with in-band backhaul or other backhaul methods. But the ITCN network remains the same.

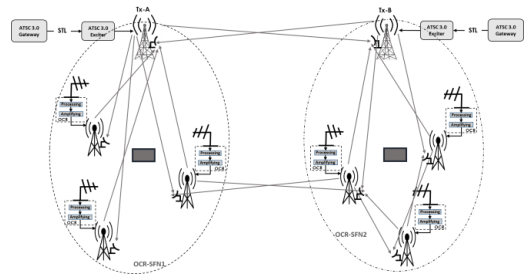


Fig. 6. A schematic diagram illustrating two interconnected ATSC 3.0 SFNs with OCR relays and ITCN.

B. ITCN and Backhaul Signal Structures

Two examples of a two-layer LDM signal structure for inter-tower network and datacasting (ITND) are illustrated in Fig. 7. Since the L2 signal is usually configured to have much higher throughput than the L1 signal, delivering the ITCN takes only part of the L2 signal capacity. The signal structure in Fig. 7(a) uses only one ATSC 3.0 physical layer pipe (PLP) [12], or time-frequency resource block, in the L2 to deliver the ITND, while the signal structure in Fig. 7(b) may use multiple PLPs, or time-frequency resource blocks, in the L2 to deliver the ITND. The ITND signal in structure in Fig. 7(b) may be more robust due to the better time-frequency diversity.

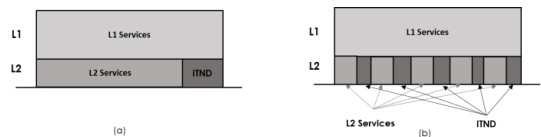


Fig. 7. Two-Layer LDM signal structure with ITCN in L2. (a) ITND in one PLP. (b) ITND in multiple PLPs.

The additional flexibility of layered structures of delivering the combined mobile, fixed, backhaul, and ITND services in two-layer LDM systems are shown in Fig. 8. There are three different services illustrated:

- SFN or non-SFN broadcasting services to mobile/fixed

terminals using LDM;

- SFN backhaul link (i.e., IDL): one-way, high data rate, high SNR for spectrum efficiency;
- ITCN: two-way communications among towers, and LDM datacasting in each tower coverage area, while each tower can transmit different data. Inter-tower networking can operate as SFN or as non-SFN multi-frequency network. ITCN could be used, for example, for datacasting.

In Fig. 8, these three services can be TDM, FDM or LDM multiplexed depending on application scenarios for efficient use of spectrum. Fig. 8(a) shows ITND TDM with LDM of L1 and L2 data. Fig. 8(b) shows LDM of two ITNDs TDM with LDM of L1 and L2. Fig. 8(c) depicts TDM of ITND and fixed broadcast services (FBS) as L2 data. Fig. 8(d) illustrates ITND TDM with LDM of mobile broadcast services (MBS) and fixed broadcast service (FBS)/in-band backhaul. Fig. 8(e) shows the TDM of three services, including LDM of mobile broadcast service (MBS)/FBS, ITND, and in-band backhaul. Fig. 8(f) depicts LDM of L1 (which is composed of MBS and ITND) and L2 (which is composed of FBS and in-band backhaul data). Fig. 8(g) illustrates LDM of MBS and L2 (which is composed of FBS, in-band backhaul, and ITND services).

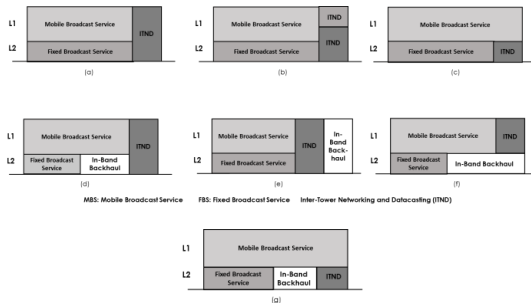


Fig. 8. Examples of two-layer LDM signal structures for delivering mobile, fixed, backhaul, and ITCN services.

In the system design, using antenna diversity allows communication with different towers (possibly at reduced SNR or data rate due to co-channel interference). ITND services can also run on multi-frequency towers, and under this circumstance, no signal cancellation is required. The system may be much simplified and with reduced system delay.

C. ITCN Interference and Control

In some scenarios, ITCN data may include three parts: (1) Network control, monitoring, and signaling data to operate the ITCN network and distributed data servers; (2) Backhaul data among transmission towers; (3) Datacasting service, where each tower can emit different data service to users. ITCN receiving antenna might receive multiple signals from more than one Tx tower, which may lead to co-channel interference. A smart adaptive antenna may be used to reduce the co-channel interference levels and multipath distortions. It will increase the ITCN data transmission capacity.

Another approach is that an ITCN network supporting

datacasting may have the other towers' transmission data stored at the receiving tower's ITCN server, which can be used to generate an interference waveform that can be used to cancel or reduce the impact of the co-channel interference signal. More discussions on signal processing and cancellation issues can be found in [23].

Most of the datacasting content/information is non-real-time, and it may be desirable to have a data server at a participating tower to store the datacasting content/information and broadcast out locally as a data-carousel. The timing and content can be controlled via the ITCN network by an ITCN server. This can also reduce the data rate requirement on the ITCN.

D. Using Three-layer LDM for ITCN and/or In-band Backhaul

When using L2 of a two-layer LDM for in-band backhaul and ITCN, there is a penalty on L2 service throughput reduction, as shown in Fig. 7. One solution to avoid the reduction of L2 throughput is to use a three-layer LDM structure, where the third layer (L3) is added for ITCN for data backhaul. This solution is shown in Fig. 9, where Tx-B/C are relay stations.

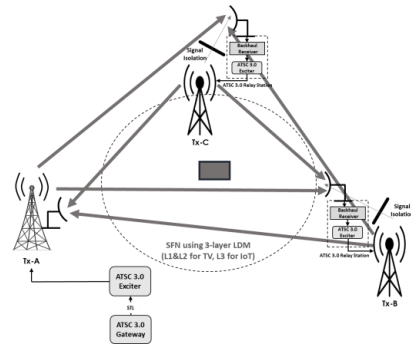


Fig. 9. A schematic diagram illustrating three-layer LDM in ATSC 3.0 SFN with ITCN.

The operation of an ITCN and in-band backhaul using 3-layer LDM in some Multicast/Broadcast Communications System (MBCS) scenarios may be as follows:

- The targeted SFN broadcast service is delivered in L1 and L2 from all transmitters: Tx-A, Tx-B, Tx-C;
- The L1 data backhaul or datacasting is delivered using L3 to an ATSC 3.0 In-Band Relay Station (IBRS) mounted on Tx-B/C. The IBRS would decode the backhauled data and re-transmit in broadcast SFN signal format and synchronize it with other SFN transmitters;
- To synchronize the emission of the L1 and L2 broadcast signals from the three transmitters, the backhaul in L3 needs to be sent to Tx-B/C earlier than the L1 and L2 data transmission time. The timing difference is easier to be set at one ATSC 3.0 frame, or any other time advance values that allows the IBRS the time needed to decode the L3 backhaul signal, re-encode and modulate the L1 signal for SFN emission;
- The L1 and L2 backhaul may transmit both the:

>

- data for L1 and L2 SFN services;
- control signaling to configure the transmission parameters of Tx-B/C, for SFN transmitter coordination, including the timing offset of Tx-B/C to optimize the SFN coverage.

- A directional high-gain antenna may be installed at a high altitude location at the IBRS, to achieve good channel condition from Tx-A/B/C, ideally a LOS channel;
- Since the receiving antenna of the IBRS may be very close to the transmission antenna of Tx-B/C, sufficient signal isolation may be needed to prevent the high-power Tx-B/C transmission signal from interfering the signal detection at the IBRS;
- More accurate L1 and L2 signal cancellation and equalization algorithms at the IBRS may be used to help to decode the backhaul signal under the interference from the Tx-B/C transmission signal;
- Two-way full-duplex ITCN services are carried out among transmitters Tx-A/B/C, through LOS paths, multiplexed either TDM or LDM with backhaul signal. Tx-A/B/C can emit different data that operating like 4G/5G networks [24]. The combination of TDM+LDM, different modulation/coding and reception conditions can provide tiered services for different robustness and reception conditions;
- L3 is not in the ATSC 3.0 standard, but it will be backwards compatible with all TV sets sold on the market, which are only required to detect L1 and L2 signals.

Examples of three-layer LDM signal structure with ITCN and in-band backhaul are illustrated in Fig. 10. In these cases, the L3 signal is a low power signal. Its data rate depends on the L1 and L2 signal cancellation accuracy and system linearity.

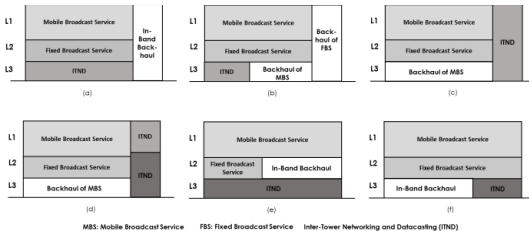


Fig. 10. Examples of three-layer LDM signal structure with in-band backhaul and ITCN in L3.

When using OCR, there is no need for in-band backhaul, Fig 10 can be much simplified. One easy implementation for ITCN with OCR is to insert ITND signal as the L3 layer. Fig. 11 illustrates the signal structure of L3 ITCN. In some implementations, the L3 can be time-frame interlaced for two-way ITCN in a half-duplex mode, rather than full-duplex mode. The time and which transmitter to emit the L3 ITND in a data frame can be pre-arranged or re-configured by the ITCN network servers. Each transmitter emits three-layer LDM or two-layer LDM over the time to form an ITCN network.

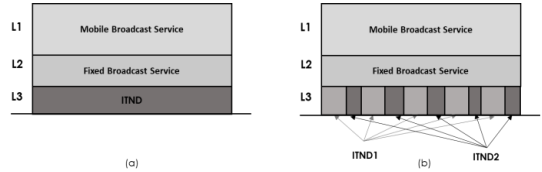


Fig. 11. Three-layer LDM signal structure for OCR-ITND service in L3: (a) one ITND. (b) multiple ITNDs.

L3 ITCN can also operate in full-duplex scheme, e.g., if the OCR inserted L3 ITCN data are using a very robust coding and modulation mode, where the SNR threshold of the L3 layer is a negative dB value, e.g., -3dB. OCR may simply insert the L3 ITCN signal as superimposed on the received and processed broadcast signal at its L3 power level. In this case, the L3 data rate may be below due to the robust coding and modulation.

E. Multi-Hop Relay

Multi-hop relay can also be realized, where an example of a two-hop OCR relay system is shown in Fig. 12. The OCRs on Tx-B/D receive the data and control signals from Tx-A, which are processed and re-transmitted to provide broadcast services. Tx-B relays the broadcast signal as the second hop to Tx-C. The consumer receiver receives broadcast signals from all transmitters Tx-A/B/C/D. Tx-B/D communicate with Tx-A over the ITCN channel, i.e., forming a looped network infrastructure.

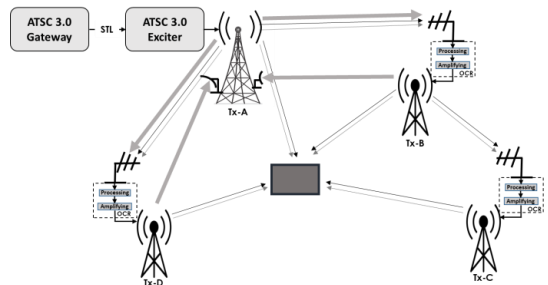


Fig. 12. An example ATSC 3.0 SFN with two-hop OCR relay using LDM.

IV. COORDINATED INTER-TOWER WIRELESS COMMUNICATIONS NETWORK

For a single broadcast operator, the in-band ITCN solution could be used where the ITCN links share the same TV channel with the broadcast services. This enables each broadcast operator to implement its own ITCN within its own channel(s), even with a single TV channel. However, for in-band solutions, the remote SFN transmitters may be affected by the loopback signal, which is the leakage signal from the broadcast transmission antenna into the ITCN receive antenna since the broadcast transmission signal may be continuously present in the time domain. With the high capacity offered by ATSC 3.0, especially with the two-layer LDM, multiple broadcast operators can multiplex their programs in fewer channels. Furthermore, shared SFN infrastructure may be more feasible

for different operators in the same area.

An alternative solution is to implement a combined ITCN using a separate TV channel for multiple broadcast operators. Each operator shares the ITCN capacity by TDM and/or FDM. In this case, time or frequency division duplex modes could be used for the bi-directional transmissions, which removes loopback signals. For the full-duplex transmission mode, highly directional antennas could be used for ITCN links that can significantly reduce the loopback signal power, potentially removing the requirement for loopback signal cancellation.

An example of the coordinated ITCN with two operators sharing the same SFN infrastructure is shown in Fig. 13.

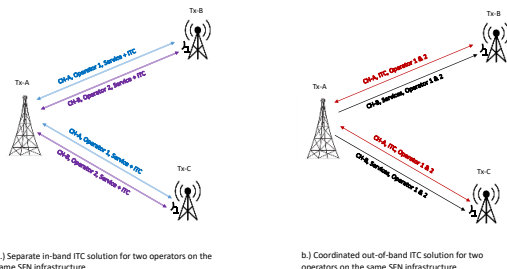


Fig. 13. Coordinated ITCN with two broadcast operators sharing the same SFN transmitters.

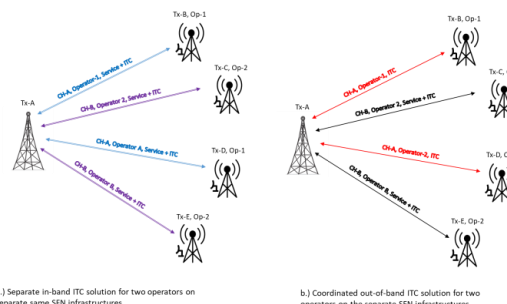


Fig. 14. Coordinated ITCN with two broadcast operators with separate SFN transmitters.

A second example of the coordinated ITCN solutions with two operators having separate SFN infrastructures is shown in Fig. 14. In this case, the ITCN links for the two broadcasters from remote SFN transmitters (Tx-B and Tx-D) to the anchor transmitter Tx-A need to be time and frequency locked. This can be achieved by using GPS time reference to control the transmission timing at Tx-B and Tx-D, which already exist in SFN transmitters.

Fig. 15 illustrates a MBCS example including local ITCN data servers at each participating TS. One or several ITCN data servers may include ITCN data storage for storing various types of data that may be transmitted to users in the TS broadcast area and another TS for re-transmitting. The stored data may include datacasting data, local advertisement, ITCN data such as ITCN backhaul among towers, local IoT data to consumers, and others. The ITCN data server may be configured to implement datacasting and/or a data carousel. Datacasting examples may include datacasting different software upgrades, local emergency alerts, weather updates, local news, etc. It takes advantage of broadcast systems one-to-many distribution capacity. Non-real-time (NRT) data, which may include TV program-related data and other data, e.g., for datacasting services, that are not TV program-related.

In some scenarios, TS participating in an ITCN network may coordinate their operations to conduct datacasting at a certain time frame. Different towers can emit different data content at the same time in an SFN environment. Towers that are not operating in a SFN may also be connected by ITCN to other towers for performing control, monitor, diagnosis, data backhaul functions. An ITCN network may be reconfigurable and scalable to extend the network or re-route ITCN data, if some network node/tower is out of service. Broadcasters may also coordinate to use a dedicated broadcast RF channel for ITCN only (without conventional broadcast service). For example, after midnight or in early morning, when traditional broadcast programs are not broadcasting (after-hour period), the entire radio frequency channel can be used for data communication/distribution. Participating broadcasters can share the network resource of the ITCN, for example using network slicing. Large and scalable inter-connected ITCN/SFN and MFN form the IITWCN, being part of the broadcast core network [25] for future broadcast internet applications.

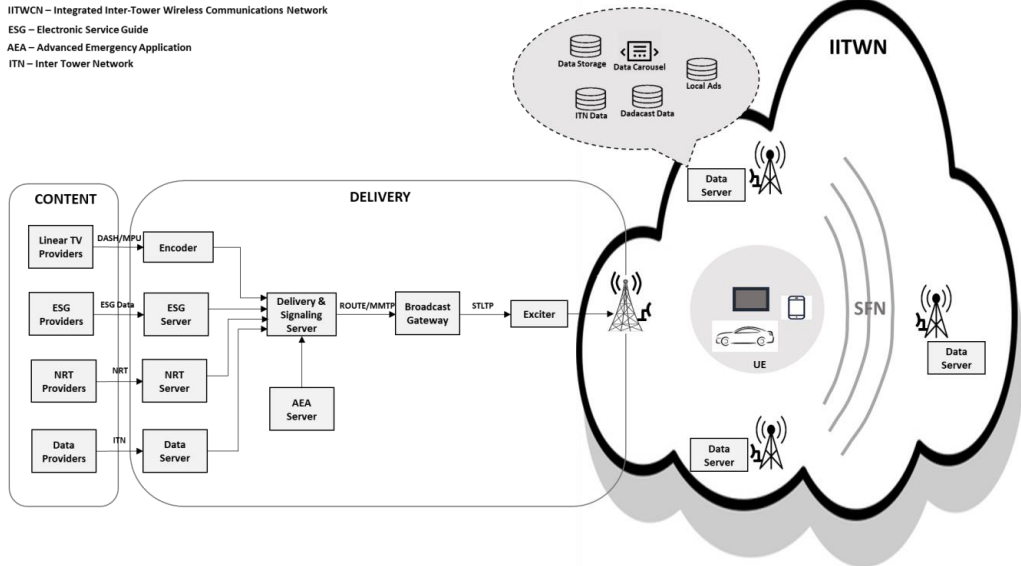


Fig. 15. Block diagram of a next generation TV station headend with MBCS containing an integrated ITCN data server.

Fig. 16 shows an example of an ITCN node at a broadcast transmitter site. An adaptive antenna can be used to maximize the main beam gain in the direction of the remote desired ITCN signal. The antenna adaptive system can also use the antenna nulls to reduce the multipath distortion of the desired signal, and more importantly to reduce the loopback signal and its multipath reflections from nearby structures. At the antenna array adaptive system block, artificial intelligence (AI) based machine learning (ML) and neural networks (NN) can be used to optimize the antenna array pattern by controlling each antenna elements' signal amplitude and phase using RF elements w_1, w_2, \dots, w_N . These elements may also perform RF filtering to reduce the adjacent channel interferences from other broadcast RF signals. The adaptive antenna array output is fed to loopback signal cancellation, where an RF analog feedback signal is used to cancel the loopback signal and related interferences and distortions.

The analog RF signal is converted to baseband for physical (PHY) layer processing, i.e., synchronization, channel estimation, digital loopback signal cancellation, demodulation, and decoding. A baseband signal feedback from the exciter is used to further suppress or cancel the loopback signal. The PHY processing output will go to the link layer processing. The output may be IP packets for the broadcast core network local server. The local server will store and control the broadcast program, backhaul, and ITCN data for relay to next node(s), datacasting data, local data, and other control data. It can also connect to a local gateway to other IP-based networks. The local network server is also fed by the broadcast scheduler and exciter to generate the RF broadcast signal waveform, followed by an RF power amplifier to generate the transmission signal to feed the broadcast transmission antennas.

An ITCN node is similar to gNB in 5G. It provides the link

between UEs and Broadcast Core Network, interfaces with broadcast PHY, and communicates with other ITCN nodes, therefore it can be seen as Broadcast Node (bNB or bcastNode [25]) - to be equivalent as gNB in 5G.

The MBCSs example shown in Fig. 16 differs from the existing wireless broadcast systems in some aspects, including:

- providing a two-way bidirectional ITCN that is integrated with a wireless broadcast infrastructure;
- having one or more embedded ITCN network servers, for example, an ITCN network server may be provided at each broadcast tower that is part of the ITCN, and may be configured to perform node and/or ITCN control functions, storage, and communicate with other ITCN towers, as well as coordinate with other towers to data carousel and datacasting local contents;
- using adaptive smart antenna arrays to improve the system performance and capacity;
- using analog interference pre-cancellation in an integrated ITCN system to improve system performance;
- using OCRs as an option to provide a physical link for ITCN and to replace in-band backhaul, thereby saving spectrum for broadcast services.

Although the example ITCNs described here primarily concern SFN operation, an ITCN may also be implemented in a multi-frequency environment, where loopback signal cancellation function is not required. Fig. 17 depicts an out-of-band ITCN network node scenario, where transmitter and receiver are in two different frequencies, suitable for non-SFN applications. In this situation, no loopback signal estimation and cancellation are necessary, which saves the signal processing efforts quite a lot at the receiver side.

An ITCN may connect multiple SFNs using the same

frequency or different frequencies, and using the infrastructures of the respective MBCS networks. In some implementations, an ITCN may be implemented using a frequency band that is separate from the frequency band of the underlying SFN or SFNs (off-band). When implemented in an SFN environment,

an ITCN may use one or more TV channels of the underlying TV broadcast network to transmit ITCN data between towers. This more complicated large-scale network is called IITWCN.

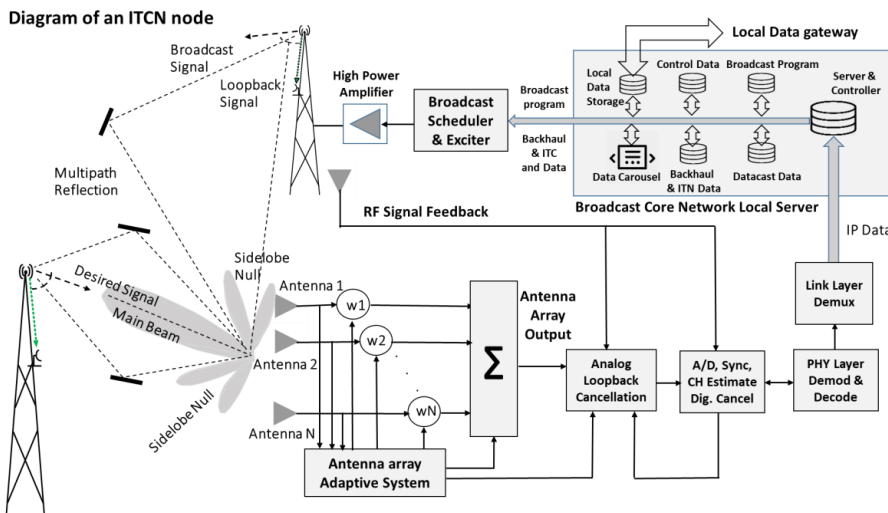


Fig. 16. A system block diagram of an in-band ITCN network node.

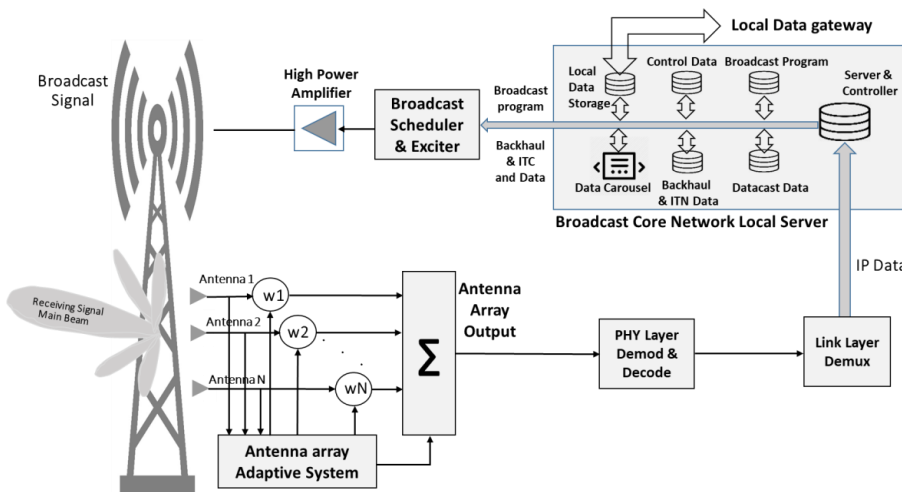


Fig. 17. A system block diagram of an out-of-band ITCN network node.

In some scenarios, one or more TV channels used for TV broadcasting during the day may be switched to ITCN communications during the TV off-hours of the TV broadcast, e.g. at nights or early mornings. In other scenarios, all or most TV channels could be switched to ITCN communications during the TV off-hours.

V. CONCLUSIONS

The concept of bi-directional integrated inter-tower wireless communications network (IITWCN) for terrestrial broadcasting and multicasting systems has been introduced. The system is backward compatible with the ATSC 3.0 NextGen TV services, causing no degradation of consumer reception. The bi-directional IITWCN is designed for inter-

tower signal transmissions of datacasting, broadcast internet, network cue, and control, etc., which specifies a large-scale wireless IP-network that inter-connects multiple SFN/ITCNs and MFNs. The wireless IITWCN extends the IDL into a scalable and configurable network embedded in a broadcast system, which becomes independent of any non-broadcasting communications infrastructure. Various IITWCN and backhaul signal structures are discussed, including the use of a third layer of LDM signal. The coordinated IITWCN was presented in the MBCS for full-fledged broadcast internet applications.

To summarize, IDL and IITWCN are part of the broadcast core-network. IDL distributes broadcast programs to transmit towers (SFN or non-SFN). It reduces broadcast operating costs by using part of the broadcast spectrum for one-way program distribution to transmission towers. Each tower will broadcast TV programs while receiving future program data at the same time on the same frequency. IITWCN is a two-way extension of IDL. It connects all broadcast towers (SFN or non-SFN) to form an IP-network for datacasting, network control, etc. Each tower can broadcast localized content, e.g., different SFN towers can emit different contents that operate like 4G/5G. All broadcast network towers form a scalable and reconfigurable IP-network embedded in a broadcast infrastructure independent to any telecommunication infrastructure.

TABLE I shows some salient aspects of SFN, IDL and IITWCN in ATSC 3.0 evolution on broadcast and broadband convergences.

TABLE I
COMPARISON OF SFN, IDL AND ITC NETWORKS

SFN broadcast	OCR or in-band distribution Link	ITCN
<ul style="list-style-type: none"> Improve service quality for mobile, handheld and indoor receptions Allow new service: IoT, connected car, datacasting One-to-many timely services for large rural areas for traffic map update, weather forecast, emergency warning 	<ul style="list-style-type: none"> Eliminate studio-to-transmitter link and inter-SFN tower feeder link spectrum requirement Reduce broadcast operating costs Spectrum sharing and reuse 	<ul style="list-style-type: none"> Scalable & configurable network embedded in a broadcast system Broadcast network cue & control that don't rely on other telecom infrastructure – surviving emergency and nature disaster Backhaul data services among towers: IP based IoT, and wide area datacasting Each tower can broadcast localized content Full duplex transmission: transmission & reception on the same frequency – improving spectrum efficiency Dynamic spectrum re-use & sharing + LDM: converging broadcast and wireless services Inter-tower network can work under SFN, OCR, or multi-frequency network environments

REFERENCES

- [1] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H.-M. Kim, J.-Y. Lee, P. Angueira, and J. Montalban, "Layered division multiplexing: theory and practice," *IEEE Trans. on Broadcasting*, vol. 62, no. 1, part II, pp. 216-232, Mar. 2016.
- [2] L. Fay, L. Michael, D. Gomez-Barquero, N. Ammar and M.W. Caldwell, "An overview of the ATSC 3.0 Physical Layer Specification," *IEEE Trans. Broadcasting*, vol. 62, no. 1, part II, pp. 159-171, Mar. 2016.
- [3] "Method and System for Wireless Data Communications", by Y. Wu et al. (October 25, 2016), US Patent 9,479,826.
- [4] J. Lee et al., "IP-Based Cooperative Services Using ATSC 3.0 Broadcast and Broadband," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 440-448, June 2020.
- [5] E. Iradier et al., "Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 503-514, June 2020.
- [6] J. Montalban et al., "Improved Semi-Blind Channel Estimation With Time Domain Cancellation for LDM-LSI," *IEEE Transactions on Broadcasting*, vol. 66, no. 3, pp. 613-619, Sept. 2020.
- [7] S. Ahn et al., "Mobile Performance Evaluation of ATSC 3.0 Physical Layer Modulation and Code Combination under TU-6 Channel," *IEEE Trans. Broadcasting*, vol. 66, no. 4, pp. 751-769, Dec. 2020.
- [8] S. Ahn et al., "Large-Scale Network Analysis in NOMA-Aided Broadcast/Unicast Joint Transmission Scenarios Considering Content Popularity," *IEEE Trans. Broadcasting*, vol. 66, no. 4, pp. 770-785, Dec. 2020.
- [9] D. Gomaz et al., "Convergence of Broadcast and Broadband in the 5G Era," *IEEE Trans. Broadcasting*, vol. 66, no. 2, part II, pp. 383-389, June 2020.
- [10] W. Li et al., "Coverage Study of ATSC 3.0 under Strong Co-Channel Interference Environment," *IEEE Trans. Broadcasting*, vol. 65, no. 1, pp. 73-82, Mar. 2019.
- [11] L. Zhang et al., "Layered-Division-Multiplexing for High Spectrum Efficiency and Service Flexibility in Next Generation ATSC 3.0 Broadcast System," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 116-123, Apr. 2019.
- [12] ATSC Standard, Doc. A/322, "Physical Layer Protocol", January 23, 2020.
- [13] S-I Park et al., "Performance Analysis of All Modulation and Code Combinations in ATSC 3.0 Physical Layer Protocol," *IEEE Trans. Broadcasting*, vol. 65, no. 2, pp. 197-210, June 2019.
- [14] L. Zhang et al., "Using Layered-Division-Multiplexing to Deliver Multi-Layer Mobile Services in ATSC 3.0," *IEEE Trans. Broadcasting*, vol. 65, no. 1, pp. 40-52, Mar. 2019.
- [15] A. Mattsson, "Single Frequency Networks in DTV," *IEEE Trans. on Broadcasting*, vol. 51, no. 4, pp. 413-422, Dec. 2005.
- [16] S. Ahn et al., "Mobile Performance Evaluation for ATSC 3.0 Physical Layer Modulation and Code Combinations Under TU-6 Channel," *IEEE Transactions on Broadcasting*, vol. 66, no. 4, pp. 752-769, Dec. 2020.
- [17] ATSC Standard, Doc. A/324, "ATSC Standard: Scheduler Studio to Transmitter Link", January 5, 2018.
- [18] W. Li, L. Zhang, Y. Wu, S. Park, N. Hur, J. Lee, "LDM in Wireless In-Band Distribution Link and In-Band Inter-Tower Communication Networks for Backhaul, IoT and Datacasting", in *Proceedings of IEEE Int'l Symposium on Broadband Multimedia Systems and Broadcasting 2020 (BMSB2020)*, October 27-29, 2020, Paris, France.
- [19] L. Zhang et al., "Using Layered Division Multiplexing for Wireless In-Band Distribution Links in Next Generation Broadcast Systems," *IEEE Transactions on Broadcasting*, vol. 67, no. 1, Mar. 2021.
- [20] S-I. Park, H. Eum, S. Park, G. Kim, Y-T. Lee, H. Kim, and W. Oh, "Novel Equalization On-Channel Repeater with Feedback Interference Canceller in Terrestrial Digital Multimedia Broadcasting System", *ETRI Journal*, vol. 31, no. 4, pp. 357-364, August 2009.
- [21] K. Salchian, Y. Wu and B. Caron, "Design Procedures and Field Test of a Distributed-Translator Network, and a Case Study for an Application of Distributed-Transmission," *IEEE Transactions on Broadcasting*, vol. 52, no. 3, pp. 281-291, Sept. 2006.
- [22] Grant, T. J., ed. *Network Topology in Command and Control. Advances in Information Security, Privacy, and Ethics*. IGI Global. pp. xvii, 228, 250. ISBN 9781466660595, 2014.
- [23] Zhihong Hong et al., "In-Band Distribution Link Signal Detection", submitted to *IEEE Int'l Symposium on Broadband Multimedia Systems and Broadcasting (BMSB'2021)*, Aug. 4-6, 2021, Chengdu, China.

- [24] D. He et al., "Overview of Physical Layer Enhancement for 5G Broadcast in Release 16," IEEE Transactions on Broadcasting, vol. 66, no. 2, pp. 471-480, June 2020.
- [25] J. Montalban et al., "Design of an IP-Based Broadcast Core-Network: Converging Broadcasters with the Connected World," submitted to IEEE Transactions on Broadcasting.

A. Eranskina

Beste argitalpen batzuk

Tesi honekin lotura zuzena duten argitalpenez gain, ondorengo zerrendak lortutako beste argitalpenak erakusten ditu.

A.1 Nazioarteko aldizkariak

BA1. Improved Semi-Blind Channel Estimation With Time Domain Cancellation for LDM-LSI

- Autoreak: Jon Montalban; Eneko Iradier; Lorenzo Fanari; Pablo Angueira; Sung-Ik Park; Sunhyoung Kwon; Namho Hur
- Aldizkaria: IEEE Transactions on Broadcasting
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/TBC.2020.2984995
- Laburpena: The adoption of OFDM as the physical layer waveform in ATSC 3.0 leaves the door open for the implementation of Single Frequency Networks (SFN). In addition, Layered Division Multiplexing (LDM), which can be understood as a low complexity approach for Non-Orthogonal Multiple Access (NOMA) techniques, has also been included as a baseline technology. These two new features can be combined to offer LDM based Local Contents (LC) in SFNs with unprecedented spectrum efficiency. Up to now, the design of a reliable channel estimation algorithm that does not require any modification of the standard has been the main challenge for the successful development of this approach. This paper aims at providing tools for satisfactory and efficient application of LDM-LSI (Local Service Insertion). In particular, in this paper, three major contributions are presented: a new semi-blind channel

estimation algorithm that takes advantage of the LDM structure of the network, a time domain cancellation technique for NOMA, and the implementation of the proposed solution in a fully compliant ATSC 3.0 transceiver.

A.2 Nazioarteko konferentziak

BK1. On the use of White Rabbit for Precise Time Transfer in 5G URLLC Networks for Factory Automation Applications

- Autoreak: Óscar Seijo; Iñaki Val; Jesus Alberto López-Fernández; Jon Montalban; Eneko Iradier
- Konferentzia: IEEE International Conference on Industrial Cyber Physical Systems (ICPS)
- Agitaletxea: IEEE
- Urtea: 2019
- DOI: 10.1109/ICPHYS.2019.8780178
- Laburpena: The implementation of 5G networks has several technological challenges, which are mainly related to the UltraReliable and Low Latency Communications (URLLC). One of these challenges is precise time transfer. Precision Time Protocol (PTP) is the most widely used protocol for precise time transfer. However, PTP performance may not be sufficient in large 5G networks. In this paper, we propose the use of white rabbit as the main technology for frequency and time transfer in 5G transport networks. However, white rabbit can only be implemented in wired links, thus the time transfer performance in wireless links may not be enough for the most challenging URLLC use cases. Therefore, we propose in this paper a modification of the white rabbit protocol that can be used in wireless communications. The proposed wireless white rabbit protocol has been tested by simulations over a single carrier point to point communication system, and different channel models. The results show significant improvements of the time transfer accuracy in Line Of Sight channels compared to other common wireless time transfer approaches and a similar performance to white rabbit over wired links.

BK2. New Semi-Blind Channel Estimation for LDM-LSI

- Autoreak: Jon Montalban; Eneko Iradier; David Romero; Pablo Angueira; Sung Ik Park; Sunhyoung Kwon; Namho Hur
- Konferentzia: IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)
- Agitaletxea: IEEE
- Urtea: 2019
- DOI: 10.1109/BMSB47279.2019.8971906
- Laburpena: Abstract: Local content insertion and viewer segmentation with proximity service information is a critical business case for broadcasting operators. This personalized service delivery will open up an opportunity for new use cases, such as local service delivery, local advertisement insertion and local emergency warning. In practice, single frequency networks (SFNs) offer a better spectrum efficiency when compared with traditional Multiple Frequency Network (MFN) approaches. Nevertheless, the addition of local content delivery can dramatically reduce that efficiency. Recently, the Layered Division Multiplexing (LDM) based Local Service Insertion (LSI) solution has been proposed as an interesting alternative for including local content in single frequency networks. Nonetheless, the required channel estimation procedure has been considered a major drawback for its successful implementation. In this work, a new semi-blind channel estimation algorithm is proposed. The algorithm takes advantage of the LDM structure and it is based on the statistical properties of the time domain Orthogonal Frequency Division Multiplexing (OFDM) frame. It proposes a solution for the major challenges that have remain unsolved so far. The paper also includes the first simulation results for this new approach.

BK3. Group-Oriented Broadcasting of Augmented Reality Services over 5G New Radio

- Autoreak: Nicola Benenati; Cristina Desogus; Pasquale Scopelliti; Eneko Iradier; Jon Montalban; Maurizio Murrone; Giuseppe Araniti; Pablo Angueira; Mauro Fadda
- Konferentzia: IEEE Broadcast Symposium (BTS)
- Agitaletxea: IEEE
- Urtea: 2019

- DOI: 10.1109/BTS45698.2019.8975412
- Laburpena: Augmented Reality applications represent the current emerging trend of broadcast services whereby users require the same data content. Broadcast applications in smart environments ask for low-latency data transmission, low-energy communication, and location- and customer-based group creation procedures. The standardization efforts done from the 3rd Generation Partnership Project (3GPP) to make the 5th generation (5G) a reality have involved also the existing Long Term Evolution (LTE) radio access technology leading to the 5G New Radio (5G-NR) standard. One of the main innovation is the definition of three different Modulation and Coding Scheme (MCS) tables to allow a differentiation according to the class of devices, grouped into five different categories based on their basic characteristics. 5G broadcast/multicast is one of the topics that is under discussion at 3GPP for 5G phase II (release 17). In this paper, authors focused on a 5G-ready LTE system, referring to real broadcast mobile urban scenarios where users are interested in Augmented Reality (AR) applications. The authors analyzed the Subgrouping Optimal Aggregate Data Rate (SubOptADR) algorithm whereby broadcast destinations are grouped into different subgroups depending on the perceived user equipment (UE) channel quality in order to maximize the Aggregate Data Rate (ADR), which is the sum of data rate values obtained by all the broadcast members. The capabilities of the algorithm are evaluated comparing LTE and 5G-NR networks, focusing on different user classes and type of devices. The paper details three envisaged AR application scenarios, describing the subgrouping optimization algorithm in 5G-NR and showing how group-oriented communications can improve spectrum efficiency in the broadcast of AR services.

BK4. Trends and Challenges in Broadcast and Broadband Convergence

- Autoreak: Lorenzo Fanari; Eneko Iradier; Jon Montalban; Pablo Angueira; Sung-Ik Park; Namho Hur; Sunhyoung Kwon
- Konferentzia: IEEE International Conference on Electrical Engineering and Photonics (EExPolytech)
- Agitaletxea: IEEE
- Urtea: 2019
- DOI: 10.1109/EExPolytech.2019.8906883

- **Laburpena:** The convergence between broadcast and broadband networks has drawn significant attention since the very beginning of their coexistence. Nonetheless, a real cooperation framework has not been successfully implemented yet due to the limits of the contemporary technologies. However, the newly proposed architectures for both broadband and broadcast allow the development of new solutions for multimedia and entertainment content delivery in multi-tier radio access networks. In fact, the convergence of broadcast and broadband technologies is one of the solutions that has been already proposed. Convergence would offer a better spectrum efficiency, improving the quality of service of the broadcasted services to mobile receivers. The main contribution of this paper is a comprehensive state of the arte of the past efforts and on top of that, the definition of the most relevant use cases for several future scenarios.

BK5. PEG-LDPC Coding for Critical Communications in Factory Automation

- **Autoreak:** Lorenzo Fanari; Eneko Iradier; Jon Montalban; Pablo Angueira; Óscar Seijo; Iñaki Val
- **Konferentzia:** IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)
- **Agitaletxea:** IEEE
- **Urtea:** 2020
- **DOI:** 10.1109/ETFA46521.2020.9211899
- **Laburpena:** Critical communication requirements included in Factory Automation applications are complex to implement due to the difficulties encountered in guaranteeing high reliability and ultra-low latencies at the same time. In this work-in-progress, a technical solution for the physical layer is proposed: the Quasi-Cyclic LDPC of the Progressive Edge Growth family (QC-PEGLDPC). This coding scheme is considered as a promising candidate due to two main factors: the good decoding performance for short packet transmissions and the low latency that can be obtained by using full parallel decoding architectures. The obtained results are compared with the 5G New Radio coding scheme, which includes LDPCs as part of the solution for Ultra Reliable Low Latency (URLLC) use cases. In these first results, QC-PEG-LDPC shows a performance improvement of 1 dB when compared with the 5G LDPC codes

for a message length of 128 bits. Latency analysis indicate that QC-PEG-LDPC could allow decoding latencies of $0.13 \mu\text{s}$ providing that the full parallel decoding architecture is enabled.

BK6. LDPC Matrix Analysis for Short Packet Transmission in Factory Automation Scenarios

- Autoreak: Lorenzo Fanari; Eneko Iradier; Jon Montalban; Pablo Angueira; Óscar Seijo; Iñaki Val
- Konferentzia: IEEE International Conference on Electrical Engineering and Photonics (EExPolytech)
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/EExPolytech50912.2020.9243861
- Laburpena: Critical application requirements proposed for Factory Automation scenarios involve demanding and simultaneous restrictions in reliability and latency. Channel coding is a basic tool to guarantee reliability but it usually involves high computation and memory resources at both transmitting and receiving sides. Among all the possible choices, Low Density Parity Check codes provide outstanding correction capacity. This paper studies two different LDPC coding approaches: 5G New Radio (5G NR) and IEEE 802.11 (WLAN). One of the drawbacks of LDPCs is their degraded performance and complex matrix adaptation for short information packets. Both 5G and 802.11 LDPCs use Quasi-Cyclic LDPC as the adaptation technique for matching the data packet size and coding matrix dimension. This paper evaluates 5G and 802.11 LDPC techniques, analyzing their structure and reliability performance for very short information messages by means of simulations. The results show that 5G NR LDPC is 1 dB closer to the Shannon limit than WLAN LDPCs, but this gain is lost for short message lengths as the ones used in Factory Automation environments. However, latency results are promising due to the opportunity of combining the analyzed techniques with new MAC techniques in order to achieve the desired reliability while not affecting latency dramatically.

BK7. Complexity Reduction Techniques for NOMA-based RRM Algorithms in 5G Networks

- Autoreak: Aritz Abuin; Eneko Iradier; Lorenzo Fanari; Jon Montalban; Pablo Angueira

- Konferentzia: IEEE International Conference on Electrical Engineering and Photonics (EEXPolytech)
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/EEXPolytech50912.2020.9243860
- Laburpena: 5G technology is expected to be a revolution in mobile communications due to its flexible physical layer (PHY). It is expected to cover a wide range of applications such as industry, virtual reality (VR) and autonomous vehicles. In particular, this work is focused in one of the main use cases of 5G: enhanced Mobile Broadband (eMBB), which targets large transmission capacities. This paper proposes algorithms that optimize the distribution of radio resources in broadcast/unicast scenarios in 5G networks using Non-Orthogonal Multiple Access (NOMA) techniques. First, a methodology to measure the complexity of those algorithms is presented and compared with Time Division Multiplexing (TDM) solutions. In addition, a specific algorithm that reaches optimum solution with less computational cost is proposed here. Results indicate that the overall complexity can be reduced more than 80% in comparison with current solutions.

BK8. Design and Performance Analysis of an ATSC 3.0 Model in NS-3

- Autoreak: Jon Montalban; Eneko Iradier; Lorenzo Fanari; Pablo Angueira; Sung-Ik. Park; Sunhyoung Kwon; Namho Hur
- Konferentzia: IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/BMSB49480.2020.9379699
- Laburpena: ATSC 3.0 has been conceived and defined as the first IP-based digital terrestrial television standard. The viewers will have access to more advanced and immersive experiences, while the broadcasters will have a new way to interact with the audience. What is more, this unique feature also paves the path to the definition of a real convergent architecture with other broadband IP networks and

the specification of new cooperative and inter-working use cases. Nevertheless, this new approach demands a thorough evaluation of the ATSC 3.0 features, not only as a point-to-multipoint (PTM) tool for media delivery, but also as an interactive player within the Internet framework. So far, there is not a tool to accomplish adequately the evaluation of ATSC 3.0 performance from a data network perspective. This work aims at filling this gap, and consequently, presents an ATSC 3.0 model that can be integrated in NS-3, a widely employed and validated discrete-event network simulator for internet systems. This tool can test the capability of ATSC 3.0 to offer new services in this interconnected heterogeneous scenarios. In the first part of the work, the paper presents the different layers that are part of this software module and how they are connected to the different parts of the network stack. Eventually, in the second part, the model is evaluated for two different scenarios and the most important parameters are studied and discussed.

BK9. Multiple Layer P-NOMA in 5G

- Autoreak: Eneko Iradier; Iñigo Bilbao; Gorka Pujana; Lorenzo Fanari; Jon Montalban; Pablo Angueira
- Konferentzia: IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/BMSB49480.2020.9379385
- Laburpena: The PHY layer presented by 3GPP in Rel-15 as 5G New Radio (NR) has considerably increased the spectrum efficiency of broadband systems, especially, due to the inclusion of Low-Density Parity-Check (LDPC) codes. Non-Orthogonal Multiple Access (NOMA) techniques can take efficiency a step further and they are currently considered a promising complementary technology for future releases. This paper addresses this technology and presents a performance evaluation of the use of multiple NOMA layers in 5G networks on a network simulator, which provides a set of new evaluation metrics. The design of the required architecture for introducing multiple layer communications in 5G is presented as the main contribution of the paper. In addition, two 5G use cases have been designed. In one of the cases, an innovative priority-based access communication architecture is proposed. Finally, the use

cases are tested in a discrete-event network level simulator and their performance is evaluated in terms of reliability, capacity and latency.

BK10. PHY Layer Performance of N-LDM for Broadcast and IoT Use Cases

- Autoreak: Gorka Pujana; Eneko Iradier; Jon Montalban; Lorenzo Fanari; Pablo Angueira
- Konferentzia: IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)
- Agitaletxea: IEEE
- Urtea: 2020
- DOI: 10.1109/BMSB49480.2020.9379456
- Laburpena: This paper presents a comprehensive performance analysis of a multiple layer LDM (N-LDM) system. Although previous works have proposed the use of N-LDM for delivering different services within a RF channel, none of them has presented results for more than three layers. What is more, a detailed analysis where the system efficiency is taken to its limit is still missing. Hence, in this work a new simulation tool has been developed, where any number of layers can be transmitted and received by using multiple layer frequency domain cancellation. On the one hand, the results address the number of services that can be simultaneously transmitted for specific user characteristics and propagation channels. On the other hand, the minimum interlayer injection level (IL) that has to be applied for correct reception has been defined and calculated for different configurations.

A.3 Liburu kapituluak

L1. Digital Terrestrial Broadcast Standards

- Autoreak: Jon Montalban; Eneko Iradier; Lorenzo Fanari; Peter Siebert
- Liburua: Wiley Encyclopedia of Electrical and Electronics Engineering
- Agitaletxea: Wiley
- Urtea: 2021

- Laburpena: The European Digital Video Broadcasting (DVB) project started in 1993 as an industry forum providing the specifications for digital broadcast. Then, the first Digital Terrestrial Television (DTT) system, DVB-Terrestrial (DVB-T), was agreed in 1997, and one year later, the first DVB-T broadcast began in Sweden and the UK. However, due to the second generation standard (DVB-T2), the data carrying capacity of a single Radio Frequency (RF) broadcast channel was really maximized. Specifically, a minimum capacity increase of 30% was achieved as well as improved SFN performances, a mechanism to reduce the peak-to-average-power ratio (PAPR) and a flexible system layer for transport streams. This article presents a system overview of the DVB-T2 standard. In particular, the general architecture of the DVB-T2 transceiver is described module by module. Moreover, several implementations and evaluation results of the standard are presented.

B. Eranskina

Curriculum

Eneko Iradierrek Telekomunikazio Ingeniaritzako Gradu eta Masterrak jaso zituen 2016an eta 2018an, hurrenez hurren, Euskal Herriko Unibertsitatean (UPV/EHU). 2015az geroztik, UPV/EHUko TSR Ikerketa Taldeko kidea da, eta gaur egun, doktorego ikaslea da. IK4-Ikerlaneko Komunikazio Sistemen taldean egon zen ikertzaile gisa 2017tik 2018ra. Doktoretza ikasketak egin bitartean, Communications Research Centre Canada (Ottawa) zentroan egin zuen estantzia. Zenbait haririk gabeko komunikazioen arloko nazioarteko aldizkari eta konferentzia entzutetsuen ikuskatzaile gisa aritu da. Gaur egungo ikerketa-interesaren artean komunikazio-sistemen geruza fisikorako teknologia berrien diseinua eta garapena, 5Grako broadcast soluzioak eta Industria 4.0rako haririk gabeko soluzioak nabari dira.

C. Eranskina

Glosarioa

1G	First Generation	Lehenengo belaunaldia
2G	Second Generation	Bigarren belaunaldia
3G	Third Generation	Hirugarren belaunaldia
3GPP	3rd Generation Partnership Project	Hirugarren belaunaldiko elkartze-proiektua
4G	Fourth Generation	Laugarren belaunaldia
5G	Fifth Generation	Bosgarren belaunaldia
6G	Sixth Generation	Seigarren belaunaldia
AA	Adimen Artifiziala	
ADB	Analogikotik digitalerako bihurgailua	
AF	Amplify-and-Forward	Anplifikatu eta aurrera egin
AMC	Adaptive Modulation Coding	Modulazio eta kodea egokitzea
AN	Artificial Noise	Zarata artifiziala
AP	Access Point	Sarbide-gunea
ATSC	Advanced Television Systems Committee	Telebista sistema aurreratuen batzordea
BCH	Bose-Chaudhuri-Hocquenghem	Bose-Chaudhuri-Hocquenghem
BDM	Bit-Division Multiplexing	Bitak zatitzearen bidezko multiplexazioa
BE	Best Effort	Esfortzurik onena
CDMA	Code Division Multiple Access	Kode banaketa bidezko sarbide anizkoitza
CH	Cluster Head	Talde nagusia
Cloud Txn	Cloud Transmission	Cloud Transmission

C-NOMA	Code-domain Non-Orthogonal Multiple Access	Kode domeinuko NOMA
CoMP	Coordinated Multi-Point	Puntu anitzeko transmisio koordinatua
CQI	Channel Quality Indicator	Kanalaren egoeraren adierazlea
CS	Critical Service	Zerbitzu kritikoa
CSI	Channel State Information	Kanalaren egoeraren informazioa
D2D	Device-to-Device	Gailutik gailura
DAB	Direct Access-Based	Sarbide zuzena
DF	Decode-and-Forward	Deskodifikatu eta aurrera egin
DSA	Dynamic Spectrum Access	Espektorako sarbide dinamikoa
DVB	Digital Video Broadcasting	Bideo digitalaren difusioa
EA	Errealitate Areagotua	
EB	Errealitate Birtuala	
eMBB	enhanced Mobile Broadband	Banda zabal mugikor hobetua
FA	Factory Automation	Automatizazio industriala
FFR	Fractional Frequency Reuse	Frekuentzia zatika berrerabiltzea
FLC	Fuzzy Logic Controller	Logika lausoko kontrolagailua
gNB	gNodeB	gNodeB
GRPA	Gain Ratio Power Allocation	Irabazi erlazioko potentzia esleitzea
HARQ	Hybrid Automatic Repeat reQuest	Errepikapen automatiko hibridoa eskatzea
HbbTV	Hybrid Broadcast Broadband TV	Transmisio hibridoko banda zabaleko telebista
IDL	In-band Distribution Link	Banda barruko banaketa lotura

IDMA	Interleave Division Multiple Access	Trukaketa banaketa anizkoitza	bidezko sarbide
IEEE	Institute of Electrical and Electronics Engineers	Ingeniari eta Institutua	Elektriko Elektronikoen
IL	Injection Level	Injekzio maila	
IMT-2020	International Mobile Telecommunications-2020	Nazioarteko telekomunikazio mugikorrek-2020	
IoE	Interconnection of Everything	Guztiaren interkonektioa	
IoT	Internet of Things	Gauzen internet	
IRS	Intelligent Reflecting Surfaces	Gainazal islatzaile adimendunak	
ITCN	Inter-Tower Communications Network	Dorren arteko komunikazio sarea	
ITU	International Telecommunication Union	Nazioarteko telekomunikazio batasuna	
ITU-R	International Telecommunication Union - Radiocommunication	Irrati komunikazioen nazioarteko telekomunikazio batasuna	
KPI	Key Performance Indicator	Errendimenduaren funtsezko adierazlea	
LDM	Layered Division Multiplexing	Geruzatan banatzearen bidezko multiplexazioa	
LDS-CDMA	Low-Density Spreading CDMA	Dentsitate baxuko hedapenean oinarritutako CDMA	
LDS-OFDM	Low-Density Spreading-based OFDM	Dentsitate baxuko hedapenean oinarritutako OFDM	
LL	Lower Layer	Beheko geruza	
LOS	Line-of-Sight	Ikusmen zuzena	
LTD	Lurreko Telebista Digitala		
LTE	Long Term Evolution	Epe luzeko bilakaera	
MAC	Medium Access Control	Ingurunerako kontrola	sarbide

MCS	Modulation and Code Scheme	Modulazio eta kode eskema
MCTS	Monte Carlo Tree Search	Montecarloko zuhaitzen bilaketa
MIMO	Multiple Input Multiple Output	Sarrera anizkoitza irteera anizkoitza
ML	Machine Learning	Ikasketa automatikoa
mmWaves	millimeter frequency bands	Frekuentzia milimetrikoen banda
mURLLC	massive ultra-reliable low latency communications	Latentzia baxuko komunikazio masibo ultra fidagarriak
MUST	Multiuser Superposition Transmission	Erabiltzaile anitzeko gainjartzearen transmisioa
NAICS	Network Assisted Interference Cancellation and Suppression	Sarek lagundutako interferentziak ezeztatzea eta ezabatzea
NLOS	Non-Line-of-Sight	Ikusmen zuzenik ez
NOMA	Non-Orthogonal Multiple Access	Sarbide anizkoitz ez-ortogonala
NR	New Radio	Irrati berria
NUC	Non Uniform Constellation	Konstelazio ez uniforme
OFDMA	Orthogonal Frequency Division Multiple Access	Frekuentzia ortogonaleko banaketa bidezko sarbide anizkoitza
OMA	Orthogonal Multiple Access	Sarbide anizkoitz ortogonala
OSI	Open Systems Interconnection	Interkonexio-sistema irekiak
PA	Process Automation	Prozesu automatizazioa
PDMA	Pattern Division Multiple Access	Patroi banaketa bidezko sarbide anizkoitza
PER	Packet Error Rate	Paketeen errore tasa
PHY	Physical Layer	Geruza fisikoa
PLR	Packet Loss Rate	Galdutako pakete tasa

P-NOMA	Power-domain Non-Orthogonal Multiple Access	Potentzia domeinuko NOMA
PTM	Point-to-Multipoint	Puntutik puntu anitzera
QC	Quantum Computing	Konputazio kuantikoa
QoS	Quality of Service	Kalitate-zerbitzua
QPSK	Quadrature Phase Shift Keying	Koadratura-faseko desplazamenduagatiko kodifikazioa
RAN	Radio Access Network	Irrati bidezko sarbide- sarea
RAT	Radio Access Technol- ogy	Irrati bidezko sarbide- teknologia
RB	Resource Block	Baliabide blokea
RE	Resource Element	Baliabide elementua
RRM	Radio Resource Man- agement	Irrati-baliabideen kudeaketa
SC	Superposition Coding	Gainjartze- kodifikazioa
SCMA	Sparse Code Multiple Acces	Kode sakabanatuaren sarbide anizkoitza
SDN	Software Defined Net- working	Software bidez defini- tutako sareak
SFN	Single Frequency Net- work	Frekuentzia bakarreko sarea
SIC	Successive Interference Cancellation	Hurrenez hurreneko interferentzien ezeztatzea
SISO	Single Input Single Output	Sarrera bakarra irteera bakarra
SNR	Signal-to-Noise Ratio	Seinale/zarata erlazioa
TAS	Transmit Antenna Se- lection	Antena igorlearen hau- taketa
TDL	Tapped Delay Line	Tapping bidezko atzerapen-lerroa
TDM	Time Division Multi- plexing	Denbora banaketa bidezko multiplexazioa
TDMA	Time Division Multiple Access	Denbora banaketa bidezko sarbide anizkoitza

TR	Technical Report	Txosten teknikoa
TTI	Transmission Time Interval	Transmisio-denbora tarte
UAV	Unmanned Aerial Vehicle	Tripulaziorik gabeko aire-ibilgailua
UL	Upper Layer	Goiko geruza
URLLC	Ultra Reliable Low Latency Communications	Latentzia baxuko komunikazio ultra fidagarriak
V2V	Vehicle-to-Vehicle	Ibilgailutik ibilgailura
V2X	Vehicle-to-Everything	Ibilgailutik edozertara
VLC	Visible Light Communications	Argi ikusgarriaren komunikazioak
VNF	Virtualized Network Function	Sare funtzio birtualizatua
WI	Work Item	Lan-elementua
WiB	Wideband reuse-1	Banda zabala berrerabiltzea-1
WSN	Wireless Sensor Network	Haririk gabeko sentsoeren sarea