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Enhanced Remote Areas Communications: The Missing Scenario for 5G and Beyond 5G Networks

LUCIANO LEONEL MENDES[1], (Member, IEEE), CARLOS SALLÉ MORENO[2],
MARIA VALÉRIA MARQUEZINI[3], (Member, IEEE),
ANDRÉ MENDES CAVALCANTE[3], (Member, IEEE),
PETER NEUHAUS[4], (Graduate Student Member), JORGE SEKI[5],
NATHÁLIA FIGUEIREDO TINOCO ANICETO[5], HEIKKI KARVONEN[6], (Member, IEEE),
IVAN VIDAL[7], (Member, IEEE), FRANCISCO VALERA[7],
PRISCILA AMERICA SOLÍS MENDEZ BARRETO[8],
MARCOS FAGUNDES CAETANO[8], (Member, IEEE), WHEBERTH DAMASCENA DIAS[1],
AND GERHARD FETTWEIS[4]
[1]National Institute of Telecommunications, Santa Rita do Sapucaí 37540-000 , Brazil
[2]Accenture, 28020 Madrid, Spain
[3]Ericsson Research, Indaiatuba 13337-300, Brazil
[4]Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, 01062 Dresden, Germany
[5]CPQD, Campinas 13086-902, Brazil
[6]Center for Wireless Communications, University of Oulu, 90014 Oulu, Finland
[7]Department of Telematic Engineering, Universidad Carlos III de Madrid, 28911 Leganes, Spain
[8]Department of Computer Science, University of Brasília, Brasília 70910-900, Brazil

Corresponding author: Luciano Leonel Mendes (luciano@inatel.br)

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ABSTRACT The next generation of mobile communication system will allow a plethora of new services and use cases. By offering support for high throughput connections, low latency response and massive number of connections, the fifth generation of the mobile network will trigger applications unseen in any other network. However, one important application scenario is not being properly addressed by the players responsible for the mobile networks' standardization, that is the remote and rural areas network. This scenario requires large cells with high throughput, flexibility to opportunistically exploit free bands below 1 GHz and spectrum agility to change the operational frequency when an incumbent is detected. Incipient actions are being considered for the Release 17 but based on the new radio specification as starting point. The limitations imposed by orthogonal waveforms in the physical layers hinder the exploitation of vacant TV channels in rural and remote areas. 5G-RANGE, a Brazil-Europe bilateral cooperation project, aims at conceiving, implementing and deploying an innovative mobile network, designed to provide reliable and cost-effective connection in these regions. This network can be seamlessly integrated with the other 5G scenarios, closing the connectivity gap between the urban, rural and remote areas. Hence, 5G-RANGE network is an interesting complementary solution for beyond 5G standards. This paper presents the major achievements of the 5G-RANGE project, from the design of the physical, medium access control and network layers, to the field demonstrations. The paper also covers the business models that can be used to make the deployment of this technology a reality.

INDEX TERMS B5G, business model, proof-of-concept, remote areas network.

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I. INTRODUCTION

During the last years, the Fifth Generation of Mobile Network (5G) [1] has been heavily researched to provide support for all applications and requirements foreseen for the future mobile technologies. These applications have been organized in three main scenarios, each one with a key major requirement. The enhanced Mobile Broadband (eMBB) communications scenario [2] must provide high data rate, increasing the capacity of the network by a factor of 20 when compared with Long-Term Evolution (LTE) advanced. This means that a 5G cell must be able to provide peak data rates of up to 20 Gbps in the downlink and 10 Gbps in the uplink. The high throughput provided by eMBB relies on the wide bands available in frequencies above 20 GHz, the so called millimeter waves [3], and also on the capacity gain provided by massive Multiple-Input Multiple-Output (MIMO) [4], where arrays with high number of elements are used by Base Stations (BSs). The high operation frequencies allow small antennas to be employed on the User Equipment (UE) side, which means that manufacturers can also implement a large number of antennas on the mobile devices [5], increasing the mobile network capacity. The 3rd Generation Partnership Project (3GPP) Release 15 [6] has defined the Physical Layer (PHY) for the eMBB scenario, called New Radio (NR) [7], but 5G is more than just higher data rates and the research activities regarding 5G networks is growing.

Ultra Reliable Low Latency Communications (URLLC) [8] is another important scenario for 5G, since it will allow several new applications to run over mobile networks. The main requirement is to reduce the overall network response time to a few milliseconds, which is one order of magnitude lower than the latency observed in LTE. Low latency communication will support mission critical applications over 5G, which means that the mobile network will be used to provide real-time control of real and virtual objects. Control loop in Industry 4.0 [9], autonomous vehicle support, online gaming and use of robots in harmful environments are some of the applications for this technology. Clearly, robustness against channel impairments provided by powerful Forward Error Correction (FEC) schemes is crucial, since the information life spam cannot tolerate re-transmissions from Automatic Repeat Request (ARQ) schemes. The definitions recently presented by the 3GPP Release 16 [10] have enhanced several functions of the 5G NR and introduced new features, such as Integrated Access and Backhaul (IAB) for NR in unlicensed spectrum in the 5 GHz and 6 GHz bands, support for Industrial Internet of Things (IIoT), URLLC, and Vehicle-to-Everything (V2X) communications and positioning.

The third application scenario for 5G is the massive Machine Type Communications (mMTC) [11], where a large number of power-limited devices are expected to be connected to the network. The Internet of Things (IoT) [12] will push the number of connections to hundreds of thousands devices per cell. These IoT devices must operate with low power consumption and simple algorithms, due to complexity restrictions. Non-Orthogonal Multiple Access (NOMA) [13] is important to assure that devices can share the available resource blocks without elaborated schedulers and the complexity for decoupling the information send from each device is handled by the BS. The mMTC will be integrated into 5G in 3GPP Release 17, which is expected to be presented in 2021. This release will propose a simplified version of the NR, named NR Lite. However, the baseline for this simple PHY will be the classic Orthogonal Frequency Division Multiplexing (OFDM) [14], which hinders the Dynamic Spectrum Access (DSA) [15] due to its high Out-of-Band Emission (OOBE). Also, spectrum efficiency over long-range links is limited by the large Cyclic Prefix (CP) necessary to protect the OFDM symbols. The enhanced Remote Area Communications (eRAC) scenario requires a PHY that goes beyond the orthogonality principles. Indeed, it needs to go beyond the current 5G limitations.

The technologies introduced in 5G to support this plethora of services and applications are certainly reducing the coverage of 5G cells. Millimeters waves are prone to high attenuation [16] and, although massive MIMO beamforming can provide higher antennas gain by adapting the radiation pattern towards the desired user, it is not expected that cells operating in above 20 GHz bands can reach a radius higher than a few kilometers. The latency reduction also imposes coverage restrictions in the URLLC, since the latency budget for the PHY is in the order of microseconds to address the information ageing requirements [17] and propagation time can become a limitation. Finally, the power restrictions imposed on IoT devices for a reasonable battery life-time in the mMTC scenario can result in short links range in the uplink for these applications [11]. Clearly, small cells are going to be a reality in 5G networks [18].

The use of high frequency bands and small cells in 5G networks hinder the development of an important scenario for continental size countries, which is the eRAC [19]. In fact, the main scenarios addressed by the current 5G networks development are antipodal to what is needed to provide reliable and high quality broadband mobile networks in remote and rural areas, which is the missing scenario to be covered by Beyond 5G networks (B5G). The areas with low population density have always been a challenge for mobile operators. Up to now, mobile standards have been conceived to provide connectivity in urban areas, where the high population density provides a sufficiently large number of subscribers within a cell coverage of 10 km or less. But, in remote areas, such limited coverage would not reach enough subscribers, leading to an unaffordable cost per user. In order to be economically attractive, a remote area mobile network must have a coverage cell one order of magnitude higher than what is provided by current Fourth Generation of Mobile Network (4G).

Another problem related to the deployment of remote area networks is the high Capital Expenditure (CAPEX). Besides the high cost of installing the equipment in remote areas and providing the required infrastructure (power, backhaul, towers, etc), the frequency licenses are one of the biggest challenges. Auctions for spectrum always require high investments, impacting the Return on Investment (ROI) in remote and rural areas. In countries where auction winners are granted with national wide license, such as in UK, the operators typically leave remote areas uncovered and, since the use of the spectrum by other players is forbidden, the status quo remains unchanged for these areas. In countries where the license to provide service in an economically interesting area is linked with the compromise for providing coverage in a more economically challenging region, such as in Brazil, operators usually prefer to pay fines instead of deploying networks in remote and rural areas.

In order to modify this situation, changes in the regulations on spectrum exploitation in regions with low population density must be promoted. One approach, which is being pursued by the 5G Rural First project in UK, consists on allowing other parties to exploit the spectrum that is not being used by the operators in a given region. The shared spectrum approach is receiving support from regulators and will allow communities and small operators to organize and deploy a local network without going through the spectrum auction process [20]. Another approach that is currently being considered by the Remote Area Access Network for the 5th Generation (5G-RANGE) project [19] consists on allowing local and rural operators to exploit unused TV channels, also known as TV White Space (TVWS), as secondary network. In this case, a cognitive engine [21] must be used to identify the spectrum opportunities where the network can be deployed and also to coordinate the spectrum change when a Primary User (PU) is identified in the frequency used by the secondary network. Here, spectrum mobility and DSA are key features for a successful implementation, which means that the PHY must employ a waveform with very low OOBE without relying on RF filtering. The PHY must also provide robustness for long range coverage, while supporting high spectrum efficiency. Therefore, modern and powerful FEC schemes must be combined with MIMO techniques to provide diversity and multiplexing gains.

A 5G network for remote areas can provide several social and economic benefits. The broadband Internet access in remote areas can introduce a large parcel of the population in the Digital Age. According to the International Telecommunication Union (ITU), only 51% of the global population is connected to the Internet [22], meaning that billions of persons still live aside from the Information Age. A remote area 5G network can connect a large set of these people, providing entertainment, education and social media services. This long-range mobile network can also be used to support IoT applied to agribusiness, improving the productivity in farms. IoT can also be used in logistics for better efficiency in transportation of agricultural production, road service, and environment, cattle and disaster monitoring. Mining is another industry sector that can benefit from a remote area mobile network, where autonomous machinery can be used in harmful and dangerous situations for humans.

The 5G-RANGE project is addressing the problem of remote and rural areas coverage by conceiving, developing and deploying a new operation mode with large cell size and high throughput at the cell border. The network developed by the 5G-RANGE project can be integrated with other B5G initiatives, increasing the reach and the importance of the mobile networks. 5G-RANGE network employs techniques that goes beyond the ones developed for 5G and which have been tailored for the remote and rural area conditions. This innovative network operates in Very High Frequency (VHF) and Ultra High Frequency (UHF) vacant TV bands using a Cognitive Radio (CR) approach, where up to 24 MHz can be aggregated to provide up to 100 Mbps at 50 km distance from the BS. The 5G-RANGE Medium Access Control (MAC) has been modified from the NR to include the cognitive engine. In order to allow for spectrum mobility and DSA, 5G-RANGE uses Generalized Frequency Division Multiplexing (GFDM) [23] to achieve very low OOBE and high flexibility. Since OFDM is covered by GFDM as a corner case, this classic orthogonal waveform is also employed by the 5G-RANGE network. Polar coding, a powerful FEC scheme used to protect the NR control plane, is also used in 5G-RANGE, but for both control and data channels. This means that the 5G-RANGE PHY does not require two types of FEC encoders and decoders, simplifying the transceiver design. The frame structure is based on NR [7], but with narrower subcarriers to increase robustness against Frequency-Selective Channel (FSC). On the Network (NET) layer, an architecture to integrate the PHY and MAC layers into the 5G core network is presented, together with an innovative use case to complement the 5G-RANGE access network to support network communications beyond the boundaries of the radio cells based on Small Unmanned Aerial Vehicles (SUAVs).

The main aim of this paper is to present the overall requirements defined for the 5G-RANGE network, based on several relevant use cases and describe the techniques used in the PHY, MAC and NET layers to fulfill these requirements. The paper also brings the evolution of the Proof-of-Concept (PoC) used for real-time field demonstrations and performance evaluation.

In order to achieve these goals, the remaining of this paper is organized as following: Section II brings the challenges and requirements for a remote area mobile network, including the main use cases that will be supported by the 5G-RANGE network. Section III describes the details of the PHY layer, while Section IV covers the cognitive MAC layer. The NET layer functionalities are presented by Section V. Section VI brings the main technical definitions for each layer of the 5G-RANGE network. Section VII depicts the PoC, the demonstrations scenarios, and the field test, while the business model to exploit the 5G-RANGE network in remote and rural areas is presented in Section VIII. Finally, Section IX concludes this paper.

II. CHALLENGING REQUIREMENTS

The eRAC scenario must address the following main use cases, which are also depicted in Fig. 1:

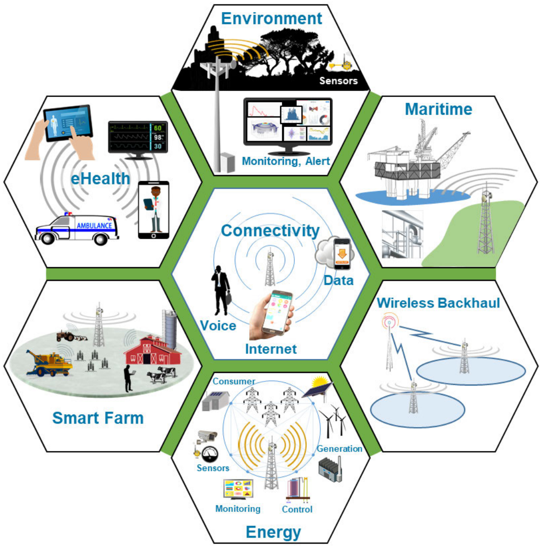


FIGURE 1. Main use cases for the eRAC scenario.

TABLE 1. Main requirements for the eRAC scenario.

Attribute	Description	KPI	
		Licensed spectrum	**Unlicensed spectrum**
Spectrum	Carrier frequency	< 3.5 GHz (priority on bands bellow 1 GHz)	
	Maximum BW	≤ 40 MHz (UL+DL)	≤ 100 MHz (UL+DL)
Spectrum Sensing	Digital TV detection threshold	---	-114 dBm in 6 MHz
	Analog TV detection threshold	---	-114 dBm in 100 kHz
	Detection threshold for low power auxiliary and wireless microphone	---	-107 dBm in 200 kHz
Traffic Model	Peak DL data rate at cell edge (one user/stationary)	≥ 100 Mbps @ 50 km	
	Average data throughput (busy hour/user)	30 kbps	
Base Station	BS maximum transmit power	Not limited for wide area mode	
	BS noise figure	5 dB	
	Layout	Single Layer: isolated super cells	
	Adjacent Channel Leakage Ratio (ACLR)	45 dB	55 dB
	# BS antennas	Up to 4 transmit and 4 receive antennas	
UE	UE transmit power	23 dBm - Power Class 3 26 dBm - Power Class 2 26 to 36 dBm – CPE	20 dBm 16 dBm if the adjacent channel requirements are not met

- **Voice and Data Connectivity:** This use case aims at providing both broadband Internet access and voice services for large areas. The vertical market for this use case is telecommunications service providers which typically sell these two services together. It is applicable in uncovered and underserved areas.
- **Smart Farms:** This use case attempts to provide capabilities for data collection and analysis, crop monitoring, production traceability, remote maintenance and diagnosis, cattle monitoring, and other services in rural areas. The vertical market for this use case is agribusiness and it is applicable in uncovered and underserved areas.
- **Wireless Backhaul:** The main goal of this use case is to exploit the TV broadcasting infrastructure available in remote communities to provide a wireless backhaul link to connect local cells to the core network. This use case also considers the connection of other technologies, such as Wireless Fidelity (Wi-Fi), Long Range (LoRa) and Sigfox with the core network. The vertical market for this application is telecommunications service providers and it is applicable in underserved areas.
- **Remote Health Care:** This use case aims at providing a communication infrastructure for health and medical assistance and monitoring in remote and rural areas. The vertical market is the health care sector and it is applicable in uncovered and underserved areas.
- **Environmental Monitoring:** This use case provides disaster alert and situational awareness for governmental and health verticals in remote regions. It is applicable mainly in uncovered areas.
- **Maritime Communications:** The aim here is to provide integration between offshore platforms and onshore facilities. The vertical markets are mining and energy in uncovered areas.
- **Smart Grid:** The goal in this use case is to enhance smart-grid connectivity and applications, allowing control of the energy flow. The vertical market is energy and it is applicable in uncovered and underserved areas.

These different use cases demand a large set of requirements that can be conflicting with each other. Table 1 contains the main requirements for the remote area applications [24].

Table 1 shows that eRAC scenario presents challenging conditions for the PHY. Since this network will operate in low populated areas, the cell coverage must be one order of magnitude larger than the one observed in 4G networks. Considering the rural and remote areas in Brazil, the cell radius must achieve 50 km from the BS in order to have enough potential subscribers to sustain the network [24]. Broadband applications for data connectivity, wireless backhaul and smart farms require high data rates over long-distance links. The network must provide at least 100 Mbps at the edge of the cell while assuring at least 30 kbps per connected device during busy hours. Since long-range links are necessary, lower frequency bands are preferable. 5G-RANGE has been conceived to operate in frequencies below 3.5 GHz, however, operation in VHF and UHF bands is desired, since the propagation characteristics at these bands are suitable for large cell coverage. Also, several available TV channels in rural and remote areas can be opportunistically used by the 5G-RANGE network. CR techniques are required to allow the 5G-RANGE network to exploit vacant TV channels without interfering with primary users. Regulation agencies around the world authorize the TVWS exploitation, but very restricted protection Key Performance Indicators (KPIs) must be addressed. One of the most challenging KPI is the Digital TV (DTV) detection threshold, where signals below the noise level must be detected to protect TV devices operating in the area. Spectrum sensing algorithms can rely on periodical structure of the DTV signals and use autocorrelation and average to reduce the influence of noise. Windowing-based energy detection algorithms [25] can also achieve acceptable performance in low Signal-to-Noise Ratio (SNR) and are good candidates for the 5G-RANGE network. Adjacent Channel Leakage Ratio (ACLR) is another challenging KPI. The ACLR values presented in Table 1, defined to protect primary users operating in adjacent channels, must be achieved without RF filter because the network must be able to use DSA and Fragmented Spectrum Allocation (FSA). Other KPIs are restricted by the standardization bodies. Although 3GPP does not limit the BS transmit power in remote areas, several countries impose transmit power restrictions. 5G-RANGE aims at using the same power levels employed in mobile networks in urban environment. The power restriction imposed to handheld device limits the coverage for smartphones. 5G-RANGE also considers Device-to-Device (D2D) communication in the handheld devices' uplink with reduced throughput. However, the 50 km link is aimed for backhauling and Fixed Wireless Access (FWA). Rooftop antennas connected to Customer Premises Equipment (CPE) are used to provide Internet access for gateways, which distributes the connectivity among other devices employing complementary technologies. There is no single technology today that can address all requirements presented in Table 1. Some technologies that can partially address the demand in remote areas are:

- **Wi-Fi** [26]: Wi-Fi is designed to be an indoor wireless network, but it has been used by small Internet providers to offer FWA in remote areas. High power wireless routers with directive antennas use Industrial Scientific and Medical (ISM) bands (typically in the 2.4 GHz band) to cover large distances. However, Wi-Fi cannot handle a large number of connected devices as well as interference with other wireless networks. This leads to a poor performance in terms of coverage and number of simultaneous connections. New standards, such as IEEE 802.11af [27] and IEEE 802.11ah [28] are designed to use CR engines to exploit TVWS. These new standards focus on low power transmissions (20 dBm) and short ranges and, therefore, they are not applicable for the eRAC scenario, but can be used as a complementary last mile solution.
- **IEEE 802.22** [27]: This standard is considered the first one to employ CR technology. However, its PHY is heavily based on Worldwide Interoperability for Microwave Access (WiMAX) [29] and it employs OFDM as air interface. The high OOBE from this waveform requires RF filtering, hindering the possibility to change the spectrum when a PU is detected. Also, the few practical implementations of this standard purely rely on a geolocation database and do not use spectrum sensing. Consequently, unauthorized transmissions cannot be detected, which means that pirate TV signals can interfere with the IEEE 802.22 network.
- **LoRa** [30]: This standard has been designed for low throughput Machine-Type Communications (MTC) applications and it cannot provide broadband Internet access. It can achieve large coverage, but at very low data rates. Furthermore, the round trip latency is around 1 s to 2 s. Nowadays, this latency is acceptable for several IoT applications, such as monitoring of machinery, soil conditions, weather and cattle, but it is unacceptable for mission critical MTC and control applications foreseen for future agribusiness applications.
- **Sigfox** [31]: This is a closed standard designed for MTC applications. It can achieve up to 50 km coverage, but the payload is limited to a few bytes and a maximum of 140 uplink transmissions per day. Sigfox can be used in IoT applications that require low data rate and that are latency insensitive, but it is not suitable for IoT applications that demand very high data rate or low latency.
- **LTE Advanced and NB-IoT** [32]: 3GPP Release 14 has introduced an evolution of the LTE lineup, which included high throughput and an IoT-oriented operation mode, called Narrow Band IoT (NB-IoT). The high throughput achieved by LTE advanced is applicable for urban environment and the NB-IoT can be used to deploy MTC services. These features allow new applications to be developed over 4G network. Although the upper MAC layer allows message timing in 100 km links, the limitations imposed by the PHY layer restricts the use of this technology in rural and remote areas. The CP length, restricted to 4.7 μs in normal mode and 16.67 μs in extended mode, cannot protect the high data rate stream from doubly-dispersive channels with delay spread that can be of several tenths of μs. Therefore, only low data rates can be achieved by 4G technology in long-rage links. Also, this technology only operates in licensed spectrum.
- **5G-NR**: 5G New Radio (5G-NR) was presented by 3GPP in Release 15 as the PHY interface for 5G networks. 5G-NR is more flexible than LTE in terms of subcarrier spacing, which can assume values of $\Delta f = 2^n 15$ kHz, with $n = 1, 2, 3, 4$. The CP length is reduced proportionally with the increment of the subcarrier spacing. This approach is an interesting solution for millimeter wave operation in Line-of-Sight (LOS) environments with high antennas gains and beamforming provided by massive MIMO. But it is not suitable for long-range links, where the multipath channel can present long delay profiles with tenths of μs. 5G-NR was also designed for operating in licensed bands, and not in TVWS. Because 5G-NR relies on OFDM, it requires RF filtering to reduce OOBE and to be compliant with the Adjacent Channel Power Ratio (ACPR) defined by the regulatory agencies. This restriction hinders 5G-NR of using DSA and FSA.
- **NR-U**: The unlicensed spectrum access introduced by the 3GPP in 5G networks, named NR for unlicensed

spectrum (NR-U) [33] will initially allow 5G networks to exploit the unlicensed spectrum in the 5/6 GHz bands and other frequencies in the Millimeter Wave (mmWave) bands will also be included. Two operational modes are possible. In the first one, called non standalone, a 5G BS operating in licensed spectrum can unload data traffic in the unlicensed spectrum, increasing the overall capacity of the network. For the second one, known as stand-alone, the 5G BS operates only in the unlicensed spectrum, without any connection with a BS operating in the licensed spectrum. This approach is interesting for deploying private 5G networks. NR-U increases the flexibility of the 5G networks, but its operation restrictions reduce its impact in remote and rural areas. The propagation losses in 5/6 GHz frequencies and the restrictions for the Effective Isotropic Radiated Power (EIRP) presented in the standard reduce the coverage area of the NR-U BS. In remote areas, the cell size must achieve tenths of kilometers to cover several subscribers and devices in order to be economically feasible. Nevertheless, NR-U is an interesting solution that can enhance the opportunities for the last mile connection and distribution of the Internet access provided by a long-range link. Hence, NR-U is a complementary technology that can be combined with the solution proposed in this paper to integrate new digital services in areas with poor or no connectivity.

The introduction of the eRAC scenario in the future B5G networks can overcome the presented limitations of the current technologies, allowing for all use cases describes in this section to be implemented in remote areas. The evolution of B5G networks can become a solution for a truly universally connected society.

III. PHY FOR REMOTE AREAS NETWORK

This section introduces the PHY explicitly designed for the eRAC scenario. The exploitation of TVWSs for the transport channel poses many challenging requirements on the PHY, which varies with the use case, as seen in Sec. II. Consequently, the PHY must employ a frame structure with a high degree of flexibility and a waveform with very low OOBE for coexistence with PUs. The control channel is assumed to be implemented on a narrow band licensed channel in the same frequency band in order to ensure constant availability for all users. In the following, the primary considerations for each subsystem of the 5G-RANGE PHY are presented.

A. WAVEFORM

The exploitation of TVWS requires a waveform with very low OOBE in order to coexist with TV stations. 3GPP specifies −45 dBc for the OOBE at the antenna and 5G-RANGE project defined −55 dBc for the OOBE when operating in unlicensed TV channels for better protection of the incumbents. Conventional waveforms, like OFDM, which is used in 4G and 5G NR, do not meet this requirement. In fact, all candidate waveforms for the 5G-RANGE PHY, i.e., OFDM, Block OFDM (B-OFDM), Filtered OFDM (F-OFDM) and GFDM, have presented OOBE above the limit, as it can be seen in Fig. 2. F-OFDM achieved good OOBE outside the occupied bandwidth, but the OOBE within the occupied bandwidth is as poor as the ones observed for the other waveforms.

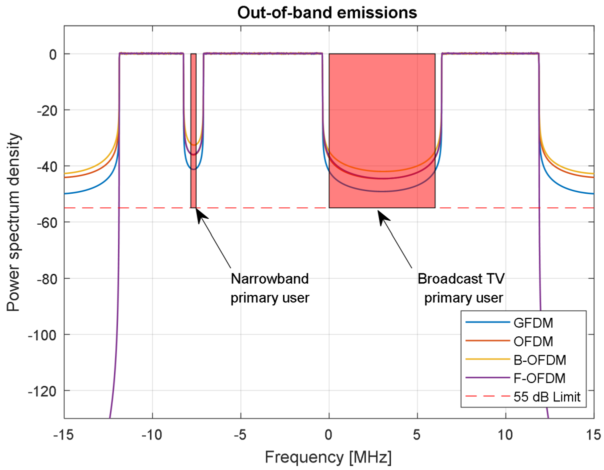


FIGURE 2. **Waveforms OOBE without time windowing.**

Employing RF filtering to reduce the OOBE is not an option, because the remote area network must be able to change its operation frequency when a PU is detected. One way to reduce the OOBE is to utilize *time-domain windowing* where the time-domain transmit signal is windowed, i.e., multiplied, with a windowing function which decays smoothly to zero prior at the beginning and end of each symbol [34]. Time-windowing can be applied to any waveform that employs CP to protect the signal against the multipath channels. Fig. 3 shows that all waveforms but B-OFDM achieved the target -55 dBc. The hard transitions within the B-OFDM blocks hinder the OOBE reduction for this waveform. F-OFDM has achieved the same OOBE as GFDM, but the former has lower spectrum efficiency in terms of CP utilization and equivalent complexity when compared with GFDM [23].

Moreover, GFDM can be understood as a generalization of OFDM, i.e., GFDM can be configured as OFDM, which allows for flexible backward compatibility with legacy networks. The good spectral behaviour presented by GFDM allows this waveform to be transmitted even in small frequency gaps between TV signals, without causing interference to the legacy technology.

A low-complexity implementation of the PHY is essential to enable an economically viable solution for emerging markets, where eRAC is more necessary. However, until recently, GFDM was considered as too complex for practical implementations, because either the number of subcarriers or subsymbols has to be odd. This restriction has been overcome by recent advances in GFDM modulation and demodulation which enable modem implementations using efficient radix-2 FFTs [35]. It is now possible to implement

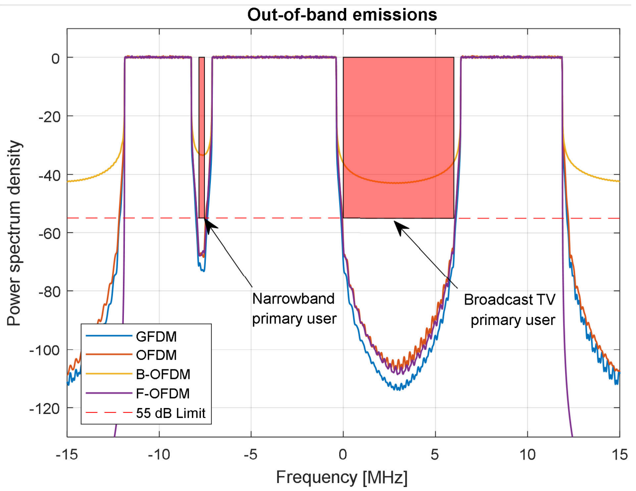


FIGURE 3. Waveforms OOBE with time windowing.

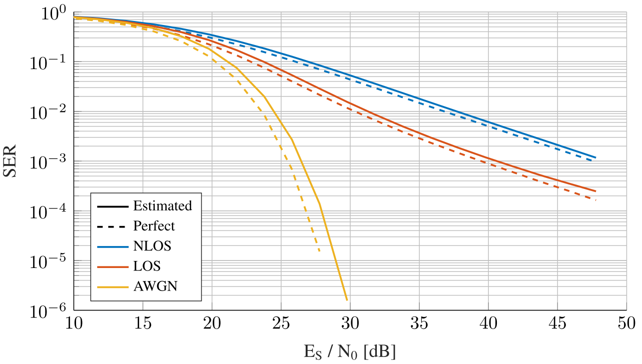


FIGURE 4. Evaluation of IFPI channel estimation algorithm [38] performance for long-range channel models from [39] and AWGN channel. Numerical results are obtained assuming block fading and by simulating 10^4 random channel realizations while employing numerology 0 of the 5G-RANGE PHY (cf. Tab. 2) in combination with 64-QAM.

flexible GFDM modems with a complexity similar to the one achieved by conventional OFDM implementations [36]. An efficient Zero-Forcing (ZF) receiver implementation for FSCs is proposed in [37]. These simplifications in the GFDM implementations allows this waveform to be used by B5G networks with insignificant impact on the overall cost of the terminals.

B. CHANNEL ESTIMATION

Accurate yet low-complexity channel estimation algorithms for the considered long-range FSCs is important for the overall system performance. Channel estimation for non-orthogonal waveforms, such as GFDM, is especially challenging because pilot observations can be distorted by the unknown payload. The Interference-Free Pilots Insertion (IFPI) scheme, considered for the 5G-RANGE receivers, promises low complexity and good performance in terms of error rate under doubly-dispersive channels [38]. The algorithm allocates the pilots in the frequency domain in the middle of the GFDM subcarriers in order to avoid Inter-carrier Interference (ICI). Fig. 4 evaluates the Symbol Error Rate (SER) performance of this algorithm for the LOS and Non-Line-of-Sight (NLOS) long-range channel models from [39] as well as for an Additive White Gaussian Noise (AWGN) channel. It can be observed that the SER performance with channel estimation is very close to the performance with perfect channel state information (denoted as *estimated* and *perfect*, respectively). An enhanced channel estimation performance of GFDM which even outperforms OFDM by up to 2.4 dB can be achieved by allocating pilots in the CP at the cost of an increased implementation complexity as shown in [40].

C. CHANNEL CODING

In order to meet the demanding requirements from Sec. II, it is necessary to find a FEC scheme that provides *i*) good error correction capabilities, *ii*) a high flexibility and *iii*) a low computational complexity. To this end, the 5G NR Low-Density Parity Check (LDPC) and polar codes are compared and the Cyclic Redundant Check (CRC) aided polar codes is considered in this paper.

A comparison of the achievable Block Error Rate (BLER) of the considered 5G NR LDPC and polar codes combined with GFDM shows a nearly identical performance over an AWGN channel, as depicted in Fig. 5. However, in some cases, the polar code slightly outperforms the LDPC code. Furthermore, a superior performance of polar codes for short block lengths and at low code rates R_{FEC} is known from the literature [41], [42]. Note that the performance at low code rates is expected to be especially important for the considered eRAC scenario in order to support long-range cells.

A recent survey, which compares LDPC and polar codes, finds that polar codes potentially offer a higher flexibility as compared to LDPC codes [42, cf. Tab. V]. Polar codes provide a high flexibility in terms of code rate R_{FEC}, as the ratio between information carrying and non-information carrying, i.e., *frozen* bits, can be chosen arbitrarily [43]. Furthermore, CRC-aided Successive Cancellation List (SCL) decoding of polar codes, which is considered to be the state-of-the-art decoding algorithm, allows vendors to flexibly balance performance and complexity by the choice of list size [44]. Moreover, in contrast to LDPC codes, the polar code block size can be chosen as any power of two without challenging optimization of the underlying prototype graph.

In terms of complexity, 5G NR specifies two FEC schemes: an LDPC code is employed for the transport channel while a polar code is employed for the control channel. Hence, it is necessary to implement two FEC decoders in each 5G NR modem. As the FEC decoder is typically the most complex signal processing block in the modem, this paper proposes to reduce the modem complexity by employing a single FEC scheme for both the transport and the control channels. A recent survey comparing Application-Specific Integrated Circuit (ASIC) implementations of both considered FEC schemes concludes that the computational complexity and efficiency of polar codes is superior, especially at low code rates [42, cf. Tab. V], despite the fact that this survey

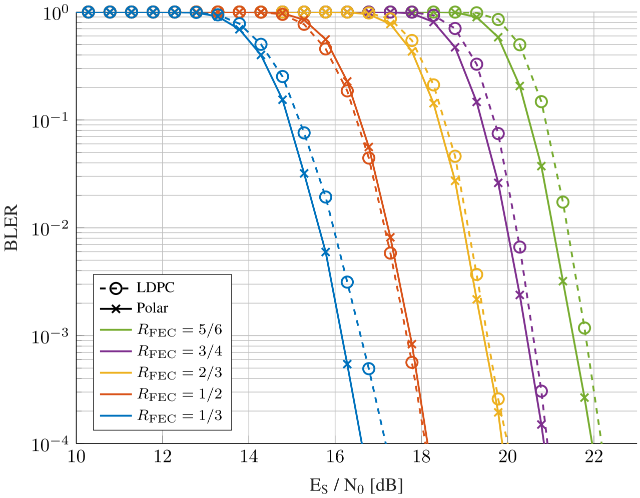


FIGURE 5. **Comparison of 5G NR LDPC and polar code over an AWGN channel employing GFDM modulation and IFPI channel estimation. Numerical results are obtained for numerology 0 of the 5G-RANGE PHY (cf. Tab. 2) in combination with 64-QAM. The block size of the LDPC and polar code is chosen to 1056 and 1024, respectively. The LDPC decoder implements the *min-sum* algorithm with a maximum of 20 iterations. The polar code decoder implements SCL decoding [44] with a list size of 8.**

does not yet consider recent advances in iterative decoding algorithms of polar codes which operate on graphs [45]–[47]. E.g., the implementation from [47] approaches the performance of CRC-aided SCL decoding while simultaneously offering advantages for implementation. Consequently, polar codes in combination with iterative decoding algorithms are expected to yield a good performance-complexity trade-off in the future.

As a result, due to slightly superior error correction capabilities, a high flexibility and a comparatively low computational complexity, the 5G NR polar code has been chosen as single FEC scheme for the proposed 5G-RANGE PHY.

D. MIMO

In order to provide the required robustness as well as to increase the effective SNR, it is necessary to utilize MIMO technologies on the PHY. Due to the considered frequencies in the VHF and UHF bands, only a moderate number of antennas at the transmitter and receiver is realistic, because of the large antenna dimensions at these frequencies. The high path loss due to the long-distance between a UE and the BS for rural and remote area scenarios is a major challenge for the PHY. GFDM can be combined with Space Time Code (STC) techniques by using the time-reversal STC [48], [49]. This scheme allows diversity gain of two times the number of receiving antennas. Typically, 2 × 2 MIMO is considered, allowing for a diversity gain of order 4.

Devices located close to the BS and that experience better channel conditions can exploit the transmit and receive antennas to increase the spectrum efficiency. In this case, spacial multiplexing algorithm is used to double the data rate using the available antennas. ZF algorithm is employed at the receiver side to decouple the data from the two transmit antennas.

E. FRAME STRUCTURE

The PHY frame structure requires specific features for the eRAC, which exploits the TVWSs. Firstly, the frame structure needs to be flexible, such that it can use any available band. This flexibility allows the use of 6, 7 or 8 MHz TV channels in accordance with the geographic region where the system is deployed. Furthermore, the frame structure should support a configurable numerology, i.e., a set of different Subcarrier Spacings (SCSs), in order to tailor the PHY to the specific use case. This allows the SCS reduction for extreme long-range use cases with limited mobility and the SCS increment for short-range uses cases with a higher mobility. An additional necessary feature of the frame structure is the ability to dynamically schedule pilots in the resource grid to avoid collisions with PUs. More details about the 5G-RANGE frame structure is presented in Sec. VI.

IV. MAC LAYER FOR REMOTE AREAS NETWORKS

The 5G-RANGE, as previously mentioned, has a challenging goal of using TVWS channels in an opportunistic and dynamic way without interfering with the PUs. Besides that, there is a demand to share the spectrum with different technologies or systems, such as Digital TV, IEEE 802.22, or with narrowband microphone. Coexistence with other technologies is a mandatory feature. Regulation bodies specify the use of cognitive mechanism to provide this coexistence, meaning that the opportunistic users have to perform the CR functions. Therefore, 5G-RANGE network must rely on CR techniques to access vacant spectrum in remote areas. CR techniques integration is a challenging task, since it must simultaneously provide coexistence with incumbent while, at the same time, achieve high spectral efficiency to deliver the necessary throughput. In addition, large cell size and the varying terrains can result in shadowing among mobile terminals, leading to the hidden terminal problem. To mitigate against this problem, 5G-RANGE system relies on cooperative spectrum sensing method, where the information from severe spatially distributed radios (or their antenna components) is used to detect the presence of the PUs. This procedure helps preventing hidden terminal problems, since the collective measurements made by a large number of devices reduce the probability of miss-detecting an incumbent user due to shadowing. The Secondary Users (SUs) send their spectrum sensing information, using the control channel to the BS, which acts as the Fusion Center (FC). At the FC, a centralized decision of channel occupancy is performed by using a fusion algorithm based on the data provided by the SUs. The cooperative spectrum sensing decision allows the BS to allocate the frequency channels minimizing the impact of the hidden terminal problem.

The new 5G-RANGE network brings some features that ease the layers integration. 3GPP recent releases provide functionalities, such as Carrier Aggregation (CA) and

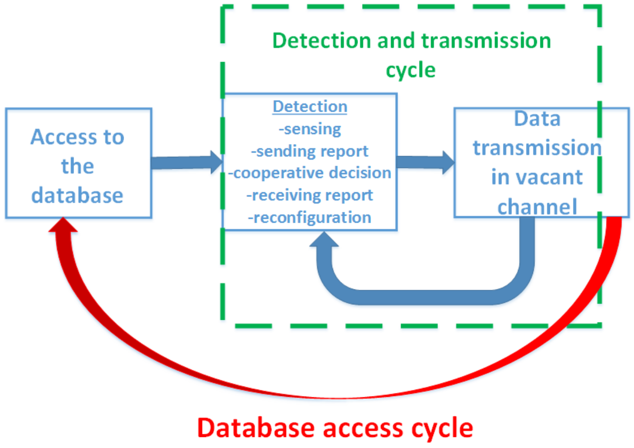


FIGURE 6. Geolocation database and spectrum sensing cycles.

License Assisted Access (LAA), that keep the control channel in a licensed band while the data channel can be defined in a non-3GPP band. This approach allows the network to off-load the data traffic in a TVWS bands, while the control channel is kept in a narrow 3GPP band [24]. Another fact is that the use of unlicensed spectrum is part of the proposed conception of the 5G, by allowing operators to improve the 5G user experience by combining licensed and unlicensed spectrum. In this case, spectrum sharing is a demand. Studies are conducted to use the ISM spectrum band, based on Listen-Before-Talk (LBT) mechanism to cope with the coexistence issue with other technologies [50], [51]. This demonstrates that the unlicensed spectrum usage is in the pathway of the 3GPP specification for the new technology, such as NR-U. Other facts are that the 5G provides carrier bandwidth up to 100 MHz for bands below 6 GHz with flexible bandwidth configuration, matching with the TVWS channel aggregation in a flexible way.

5G-RANGE must have a MAC layer with a cognitive engine that can provide narrow and wide bands detection, both in a fragmented spectrum, in an efficient way. For that, the cognitive cycle, which is an intrinsic part of CR, requires to be integrated within the 5G-RANGE protocol stack, providing intelligent and autonomous capabilities for the MAC layer. Cognitive cycle includes Geolocation Database (GDB) information access and Cooperative Spectrum Sensing (CSS) to complete GDB information for more dynamic channel access, as illustrated in Fig. 6.

Considering remote and rural areas with large coverage, the use of groups of dispersed terminals sensing information can cooperatively and reliably determine the idle spectrum holes. Depending on the number of terminals providing sensing information, this can result in overhead in the control channel, and narrowband or sub-band signal detection can magnifying this overhead, if sensing information for each sub-bands is demanded. But the CSS can minimize this overhead by using intelligent mechanisms to achieve efficient use of the control channel [52]. Cognitive core functionality requires to be implemented in the PHY and in the MAC layers. The first one performs the actual sensing measurement of the channel, and the last one controls the user plane transmissions in the downlink and uplink.

When the terminal is turned on, it starts the initial access procedure. For this, after the terminal synchronizes with a cell, it performs the random access procedure, which involves the control channel in the licensed band as part of the LAA specification. After this terminal succeed in this initial access procedure, the user plane is created with the DSA procedure, enabling SU opportunistic and dynamic access to the vacant TV channels, as long as there is data to transmit. The MAC layer performs the DSA with spectrum sharing by controlling the multiple access and resource allocation. This is done by selecting the best subcarriers to be allocated for each UEs, based on the Channel Quality Information (CQI) provided by the link adaptation procedure. The integration of CR functions adds the spectrum sensing information into the resource allocation decision process. CRs are perceived as a possible solution for the future spectrum scarcity [53], and integrating the cognitive cycle in the 5G-RANGE system results in an autonomous, spectral efficient, and intelligent CR. Besides that, this integration is an enabler to build a knowledge base using techniques such as Artificial Intelligence (AI) and machine learning, resulting in an intelligent way to control the sensing function and consolidate the received sensing data from different UEs, minimizing the control channel overhead and reducing the energy consumption [54].

Fig. 7 illustrates the general architecture of the cognitive MAC layer introduced in [55]. Having in mind the previous requirements, the possibilities for the control channel integration can be split in two procedures. The first one is the Channel State Information (CSI), which collects all information related to the UE channel measurements and reports, where the CQI report provides the channel quality information in the frequency domain. The second one, is with MAC scheduler resource allocation that controls the user bits allocation for transmission in the frequency domain. Both procedures are independent but they rely on the same information provided by the UEs. In Fig. 7, the COllaborative spectrum Sensing Optimized for Remote Areas (5G-COSORA) at the UE side provides the spectrum report. The BS receives these reports from different UEs, and performs the fusion algorithm, providing the consolidated information about the PU or other SUs detection decision. When the MAC scheduler has user data to transmit, the Dynamic spectrum and resource Allocation for Remote Areas (5G-DARA) provides the resource blocks that can be employed by the user data transmissions.

The sensing report can be more or less accurate depending on the sensing algorithm performed by the UEs [56]. In a more accurate case, the sensing report results in more bits to be sent in the control channel. This can result in traffic jamming at the narrow band control channel. The CSS complementing the geolocation database can minimize the request for accurate sensing report, and finally, the knowledge base information can be used in the decision to request sensing measurement and report only for a small set of

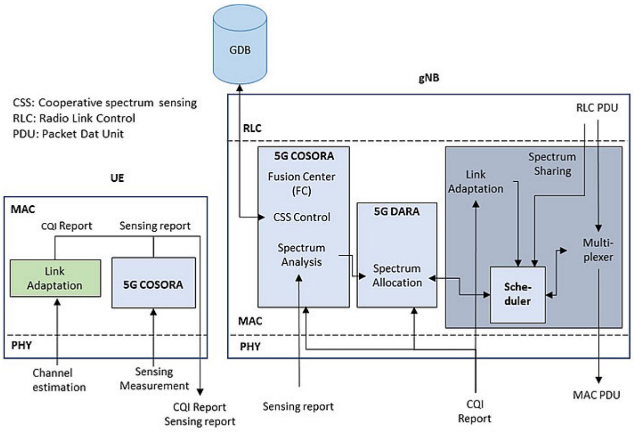


FIGURE 7. **Architecture of the cognitive MAC layer [55].**

terminals, minimizing the control channel overhead. CSS also provides consolidated information of idle spectrum holes, and the MAC scheduler consults this information to perform the frequency domain resource allocation for each terminal. The integration of the cognitive cycle results in two quasi-independent process, the CSS and the DSA.

To select spectrum sensing technique, which information is needed at MAC layer, 5G-RANGE evaluated the performance of Energy Detection (ED)-based method (Window-Based Energy Detection (WIBA)) and eigenvalue-based detection (Gershgorin Radii and Centers Ratio (GRCR) [57]). Typically,ED methods must have estimation of the noise level to set a threshold for the signal detection decision making. The ED method can estimate the noise level, i.e., it does not need to be provided beforehand. WIBA was found to provide better spectrum sensing performance than the reference technique Localization Algorithm based on Double-thresholding (LAD) [57]. In eigenvalue-based detection case, GRCR was found to be best and fairly simple test statistic for cooperative or multi-antenna spectrum sensing. Although simple and full-blind, GRCR is robust against dynamical noise and received signal powers, it exhibits Constant False Alarm Rate (CFAR) property and outperforms the most common full-blind detectors in the literature. Therefore, WIBA and GRCR method are qualified candidates for B5G networks that exploit TVWS. Cooperative spectrum sensing will improve the performance of these techniques [57]. Due to the variable characteristics of the eRAC scenario (mobility of UEs and varying terrains), it is important to use cooperative spectrum sensing techniques to minimize the hidden terminal problem, as was previously discussed.

V. NETWORK LAYER FOR REMOTE AREAS

The aim of the 5G-RANGE network layer is to provide end-user terminals with secure end-to-end Internet Protocol (IP) network connectivity, considering and complementing the solutions adopted at the lower levels, i.e., the PHY and the cognitive MAC layers. More concretely, besides network connectivity, the network layer covers the following fundamental aspects: supporting access to operator-specific services (e.g., IP telephony) as well as to Internet services (e.g., web browsing, email, video-on-demand, etc.), which may be provided from external data networks; handling UE mobility, not only within the 5G-RANGE access network domain, but also across other access networks that may be available in the UE vicinity; and securing the network access connectivity, considering confidentiality, integrity and authentication of network layer communications. Figure 8 presents the architectural view of the 5G-RANGE network layer that supports all use cases described in Sec. II.

The network layer includes the components of a 5G core network, as defined by 3GPP [58], [59], which supports the connectivity of the end-user terminals via the 5G-RANGE access network. These terminals can be directly connected to the access network, or can get network access connectivity through a gateway. An IP Multimedia Subsystem (IMS) core [60] enables the provision of IP telephony services to the subscribers that connect to the 5G core network via the 5G-RANGE access network.

Given that 5G-RANGE access network is a novel technology, it is still unclear whether future standardization processes will consider it as a 3GPP access network. Therefore, the 5G-RANGE network layer considers the different options specified by 3GPP to connect the access network to the 5G core network, which can be either as a 3GPP or as non-3GPP access [61]. As an example, Fig. 8 illustrates the case where the 5G-RANGE access network is considered as a non-3GPP access network. In this case, a Non-3GPP Inter-Working Function (N3IWF) would enable the interconnection of the 5G-RANGE access network to the 5G core network.

Additionally, in concordance with 3GPP specifications, the network layer architecture considers that the different components of the 5G core network and the IMS core can be virtualized and executed as Virtual Network Functions (VNFs). The virtualization of functions is a relevant technology in the field of 5G networking, being subject to standardization at European Telecommunications Standards Institute (ETSI) with the name of Network Functions Virtualization (NFV) [62]. The 5G-RANGE network layer adopts this technology: the purpose of the transversal Management and Orchestration (MANO) functionalities, shown in Figure 8, is precisely to support the deployment of the different components of the network layer (particularly the core network and the IMS core) as VNFs.

A. EXTENSIONS TO THE NETWORK LAYER

Besides the definition or the network layer architecture and the protocol stacks, 5G-RANGE is also exploring a cost-effective approach to complement the network infrastructure offered by the access network, e.g., to support network communications beyond the boundaries of the 5G-RANGE radio cells. This may be useful in different use cases related to 5G communications in remote areas, but in 5G-RANGE it has been particularized for the voice and data connectivity over long distances use case and the smart farming for remote areas

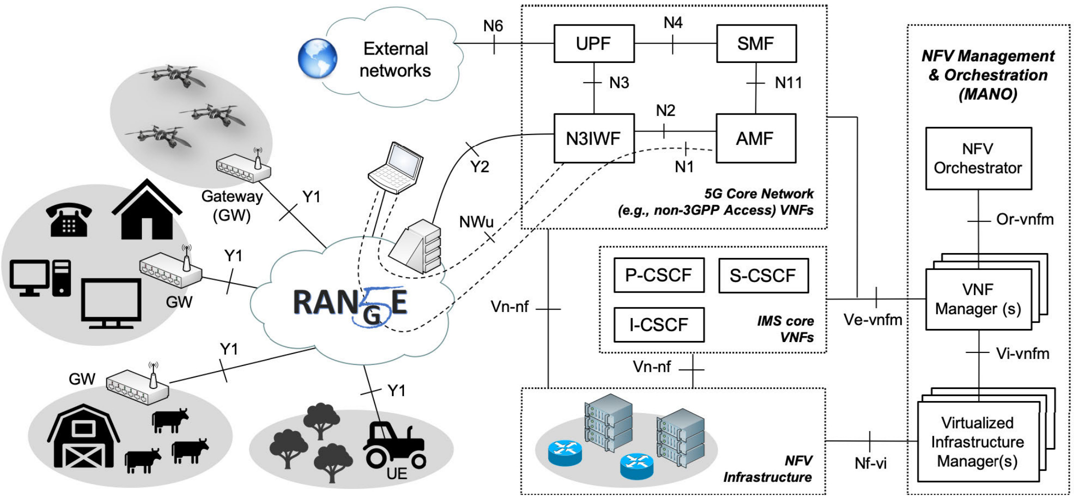


FIGURE 8. Overview of the network-level architecture of 5G-RANGE.

use case. In these cases, a number of SUAVs are deployed over a delimited geographic area. Ground units and vehicles (e.g., harvesters, tractors, sprayers, etc.) can also be exploited to support the deployment. These devices would be interconnected to build an ad-hoc network infrastructure, and would complement the functionalities of the 5G-RANGE access network, that is, providing network communications over that area, and supporting the automated and flexible deployment of VNFs and services under the control of the 5G-RANGE MANO system. Figure 9 shows an illustrative example of the application of this approach to facilitate the provision of voice and data connectivity over long distances, where network connectivity is to be provided to users participating in a festive event in a remote area beyond the limits of a 5G-RANGE radio cell. A specific Open Source network emulator (VENUE, [63]) has been developed within the context of 5G-RANGE in order to be able to validate this type of scenarios in laboratory environments, including SUAVs with on-boarded resource constrained single board computers with VNFs that are orchestrated by the MANO platform together with the rest of network components.

B. IMPLEMENTATION OF THE NETWORK LAYER

Regarding the MANO functions and the NFV infrastructure components of Figure 8, we have conducted the deployment of a functional NFV MANO platform based on open source technologies. To this purpose, we have followed the methodology presented in [64]. The MANO platform will serve to support the validation of the network layer components. It will also be considered as an enabling platform to support the PoC activities of the 5G-RANGE project.

The MANO platform has been deployed in the 5G Telefonica Open Network Innovation Centre (5TONIC), based in Madrid (Spain), using open source technologies. In particular, it has been installed in a server computer using two independent virtual machines: one hosting an installation of Open Source MANO, which is an open-source implementation of a MANO stack aligned with the ETSI NFV reference specifications; and a second one providing an OpenStack controller, acting as a virtual infrastructure manager. This MANO stack controls the compute, storage and network resources provided by a cloud of two server computers, connected through a Gb/S Ethernet switch.

With respect to the development of the network layer components of Figure 8, a basic prototype of a UE and a core network have been implemented. It is important to highlight that these components have been developed with the purpose of supporting testing and trialing processes in the PoC. Therefore, they are not intended to provide a complete implementation of a 3GPP UE and a 5G core network. In particular, they support the user-plane protocol stack defined by 3GPP for non-3GPP access networks, which is based on Generic Routing Encapsulation (GRE) [65] and Internet Protocol Security (IPsec) [66]. Regarding the core network component, it provides the basic forwarding functionality of a N3IWF and a User Plane Function (UPF), as defined by 3GPP (more details on the architectural components and the protocol stack for non-3GPP access networks can be found in [58]). To ease their utilization in the PoC, both components have been implemented as virtual machines.

In addition, a preliminary functional validation of the developed components has been performed. With this purpose, the UE and the core network prototypes were interconnected through a routing function, which represented the 5G-RANGE access network. Finally, the core network was connected to an external equipment using a Gb/s link. The final setup is depicted in Figure 10.

This setup allows the measurement of the maximum average throughput and the Round Trip Time (RTT) that could be achieved between the UE and the external equipment. The results are collected in Figure 11. Regarding the maximum

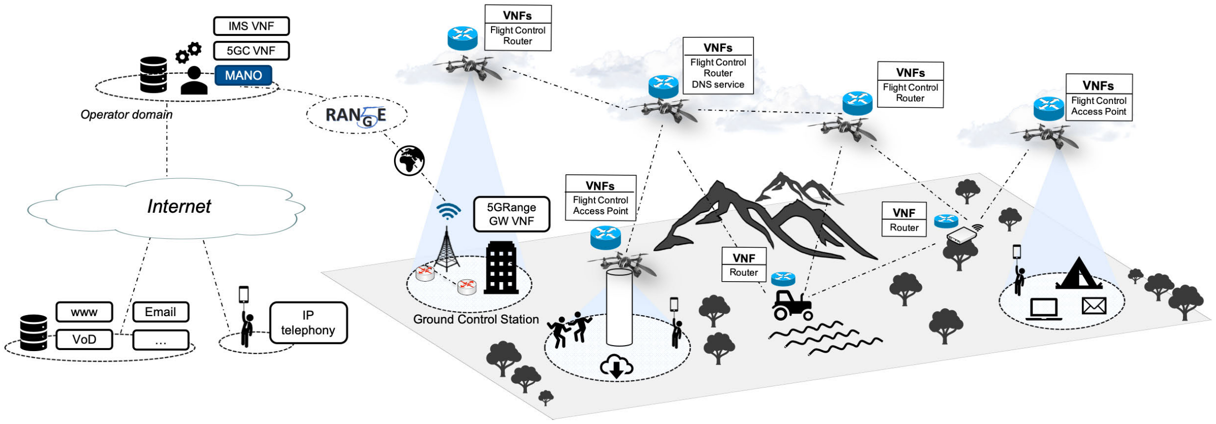


FIGURE 9. Using aerial/ground units to aid voice and data connectivity.

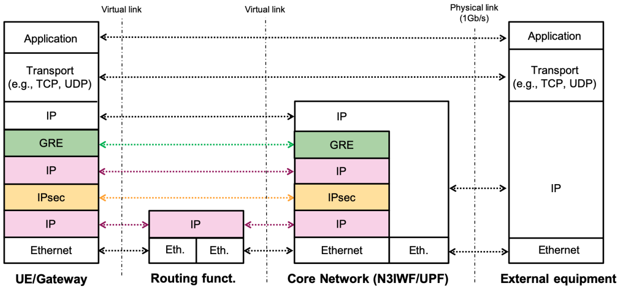


FIGURE 10. Evaluation of network layer components.

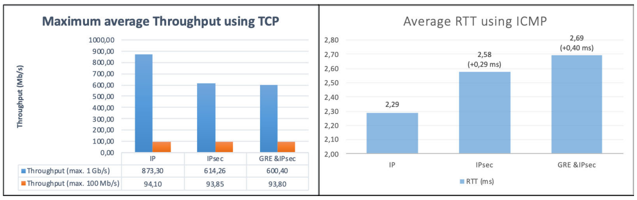


FIGURE 11. Maximum average throughput and RTT.

average throughput, it is possible to observe that it is in the order of 600Mb/s. This represents a reduction of approximately 31% with respect to the throughput that can be achieved without using GRE tunnelling and IPsec (these protocols cause processing and message overheads). Still, the preliminary validation results indicate that the implementation of the UE and the core network can provide an average throughput above 100 Mb/s, which is the expected maximum throughput of the 5G-RANGE access network (in fact, with a 100 Mb/s link between the core network and the external equipment, the implementation achieves a throughput of 93.8 Mb/s). On the other hand, the impact on the RTT due to the tunnelling and cryptographic operations done by GRE and IPsec is limited, although a more appropriate evaluation of the RTT metric is still needed, considering more realistic scenarios with background traffic.

As a first step towards validating the 5G-RANGE network layer architecture from a practical perspective, as well as its extensions related with the utilization of SUAVs and resource constrained devices, several experiments have been done using the NFV platform deployed at 5TONIC and the prototype implementation of the aforementioned components. In particular, in [67] the authors present a use case where an IP telephony service is to be provided in an area beyond the radio coverage of the 5G-RANGE access network. This use case has been realized in laboratory conditions. The results served as a first step to demonstrate the practical feasibility of using NFV and resource constrained devices to support voice and data connectivity over long distances. Motivated by these results, and considering the lessons learned from this work, in [68] the authors conducted a theoretical analysis of the main challenges and hurdles to NFV operations in resource constrained environments, with a main focus on the transport protocol options above the network layer.

VI. TECHNICAL DEFINITIONS FOR THE 5G-RANGE NETWORK

The results achieved by the 5G-RANGE project for each layer of the proposed mobile communication network show that a 5G network for remote areas is technically and economically feasible. In this section, all technical definitions for each layer of the 5G-RANGE network are summarized.

A. PHY Layer DEFINITIONS

The 5G-RANGE PHY layer must be flexible to support all use cases expected to be used in remote and rural areas. The 5G-NR has been used as baseline for the 5G-RANGE PHY, but the numerology has been tailored for the remote and rural area scenario and new techniques have been added to address the challenge of providing high throughput data rate in remote areas.

The first important change is the subcarrier spacing. 5G-NR enlarges the subcarrier spacing starting from the LTE 15 kHz. This is an interesting approach to achieve high throughput in short channel delay profiles. However, for long-range operation, where the channel delay profile

TABLE 2. 5G-RANGE PHY specifications.

	Numerology					
Parameter	0	1	2	3	4	5
Sampling [MHz]	30.72					
Waveform	GFDM (OFDM as corner case)					
GFDM filter	Raised cosine					
Roll-off factor	0					
Windowing	Raised cosine					
Δf [kHz]	1.875	3.75	7.5	15	30	30
Subcarriers (SCs)	16K	8K	4K	2K	1K	1K
Active SCs	12672	6336	3168	1584	792	792
Subsymbols (SSs)	4	4	4	4	4	2
CP [μs]	141.7	70.8	35.4	17.7	8.9	4.4
CS [μs]	25	12.5	6.25	3.13	1.56	0.78
Symbol [ms]	2.13	1.07	0.53	0.27	0.13	0.067
CP/CS effic.	92.75%					
Mapping	4, 16, 64 or 256-QAM					
Range [km]	240	120	60	30	15	7.5
Speed [km/h]	7.5	15	30	60	120	240
Pilot spacing SCs	4					8
Pilot spacing SSs	2	4				
Uncoded Gross Bit Rate for 24 MHz band [Mbps] - excluding pilots						
4-QAM	39	41	41	41	41	42
16-QAM	77	82	82	82	82	84
64-QAM	115	124	124	124	124	126
256-QAM	154	165	165	165	165	169

can have multipaths delayed by hundreds of microseconds, narrower subcarriers are more interesting, since this approach leads to a longer symbol in the time-domain, which allows for large CP length and better protection against frequency-selective channels. Also, the long symbol duration allows for adding the Cyclic Suffix (CS) for time widowing without severely reducing the overall spectrum efficiency. Table 2 presents the main parameters of the PHY layer defined for the 5G-RANGE network.

5G-RANGE adopted GFDM as waveform because of its flexibility and robustness against doubly-dispersive channels. Since GFDM covers OFDM as a corner case, the 5G-RANGE PHY also employs this conventional waveform. This solution is interesting because it allows the 5G-RANGE time-frequency grid to be compatible with LTE and 5G-NR. The wide selection of subcarrier spacing provides robustness against long multipath channels or fast time-variant channels. This means that 5G-RANGE can couple with doubly-dispersive channels in accordance with its most demanding characteristic.

The Polar code has been selected for the FEC subsystem because of its robustness, affordable complexity and flexibility in terms of code rate and block size. Table 3 brings the FEC definitions adopted for the 5G-RANGE.

MIMO is essential to provide high spectrum efficiency and robustness for any mobile communication network and 5G-RANGE exploits this technique to provide multiplexing and diversity gains, in accordance with the conditions of the users link. Since 5G-RANGE operates in UHF bands, the number of transmit and receive antennas is limited by its size. Vertical and horizontal polarizations are exploited in both transmit antennas, allowing 5G-RANGE to operate with up to 4 × 4 MIMO. However, all the main requirements

TABLE 3. FEC parameters for the 5G-RANGE network.

Parameter	Description
FEC Scheme	5G-NR CRC aided Polar code according to [69].
Encoder	Arikan Systematic Encoder [70].
Decoder	Successive cancellation list.
Rate match	Circular buffer.
Interleaver	Upper triangular matrix.
Block size	256, 512, 1024, 2048, 4096, 8192
Code rate	1/3, 1/2, 2/3, 3/4, 5/6.
List size	1, 2, 4, 8, 16, 32.

TABLE 4. FEC parameters for the 5G-RANGE network.

Diversity Scheme	
System order	2x2, 2x1 and 1x2 operation.
STC rate	1
Spatial Multiplexing Scheme	
System order	2x2 and 4x4
Channel condition number	<10 dB (<20 dB with degradation).
Layer precoding matrix	as specified in TS 36.211 [71].

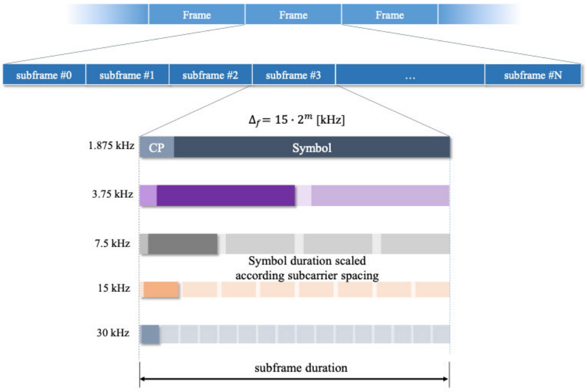


FIGURE 12. Frame structure in time domain showing the alignment of multiple numerologies.

are addressed with 2 × 2 MIMO. 5G-RANGE uses spatial multiplexing MIMO for the users that present high SNR, i.e., the users close to the BS. The 5G-RANGE BS automatically switch to STC MIMO for the users experimenting challenging channels frequency response and with low SNR, i.e., located far away from the BS. With this approach, higher spectrum efficiency is provided for users with good channel conditions and high robustness is achieved for the users with more challenging channels conditions. Table 4 shows the specifications for the MIMO system used by the 5G-RANGE network.

B. MAC LAYER DEFINITIONS

The frame structure for the 5G-RANGE network has been based on the 5G-NR definitions, but with adaptations for the remote and rural areas scenarios. The subframe structure is scalable to accommodate the new symbols duration presented in Table 2. Figure 12 depicts the 5G-RANGE time frame structure.

The 5G-RANGE PHY uses a time-frequency grid composed by subcarriers and symbols where information is

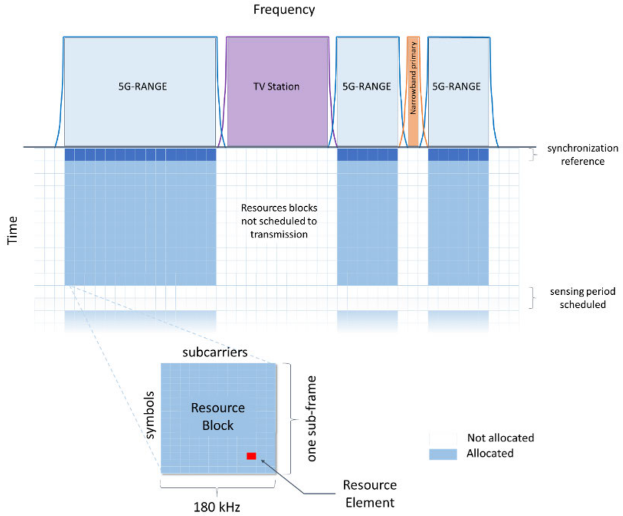


FIGURE 13. Time-frequency grid of the of the 5G-RANGE network.

TABLE 5. Functionalities of the 5G-RANGE cognitive cycle.

Cognitive Cycle Function	Function Description
Spectrum Sensing	Sensing measurement executed by UEs and BS, providing SS reports.
Spectrum Analysis	Fuses all SS reports to find the available UHF bands.
Spectrum Allocation	Allocates the available UHF bands to the UEs.
Spectrum Sharing	Transmits data of different UEs in the radio environment and implements the spectrum sharing policy.
Spectrum Switch	Performs the spectrum migration once a primary user is detected in the band occupied by the network.
Spectrum Idling	Defines which UEs shall be in idle stage, being able to receive only control messages from the BS.

organized and transmitted in a similar manner than in 5G NR. TVWS exploitation requires protection to the bands occupied by primary users. This protection is achieved by the fragmented spectrum allocation, where groups of subcarriers in the available bands are selected to transmit data and the subcarriers in the bands occupied by the primary users are turned off. This approach allows fine granularity in spectrum usage and allows for efficiently avoiding narrow band incumbents. Figure 13 depicts the frequency-time resource grid. The 5G-RANGE PHY allows allocation with the granularity of one Resource Block (RB), which is composed by a fixed bandwidth of 180 kHz. This RB is equivalent to 12 subcarriers with 15 kHz frequency spacing, therefore, the same used by LTE or 5G-NR in the narrower configuration. However, as opposed to 5G-NR, RBs are not scaled with the subcarriers and they remain constant for any numerology. In the time-domain, the 5G-RANGE RBs have a duration of one sub-frame.

The 5G-RANGE time-frequency grid has a silent period that is used for in-band Spectrum Sensing (SS), necessary to detect the presence of incumbents operating in the same band occupied by the mobile network. Also, the 5G-RANGE network must sense for other spectrum opportunities within the UHF band. Hence, the SS mechanism is a key feature of the 5G-RANGE network and several techniques have been analysed in terms of detection capabilities and implementation complexity [57]. Since the regulators demand detection of TV signals with very low power, the techniques that use information about the primary signal and the cooperative sensing are interesting candidates [72]. The decision about which SS technique to be used is a vendor decision and the 5G-RANGE project does not specify one specific approach. Nevertheless, different techniques have been studied and the WIBA energy detector showed interesting trade-off between performance and complexity [25].

The cooperative spectrum sensing and the dynamic spectrum access is orchestrated by the cognitive cycle defined for the 5G-RANGE MAC. The cognitive cycle defines which devices shall perform the spectrum sensing and in what UHF channels, which channels can be exploited by the mobile network, to which users each subband shall be allocated, and which devices shall be in idle and active stage. Table 5 describes the main functionalities of the 5G-RANGE cognitive cycle.

The controls messages and the SS are transmitted by the BS and UEs, respectively, using the control channel, which is a narrow 1.4 MHz licensed band. The control channel is also used by the UEs to report their CQI, which is used by the MAC layer to define the best Modulation Coding Scheme (MCS) for each user at every frame.

C. NETWORK LAYER DEFINITIONS

The network layer must provide a flexible, end-to-end connectivity platform, on top of which different services can be deployed and provided to the 5G-RANGE users. These services do not only include those traditionally provided by telecommunication operators, such as IP telephony or live IP television. The connectivity platform must be flexible enough to support the user access to services that are available in the Internet, e.g., web browsing, video-on-demand, or music streaming services.

On the other hand, the project ambitions to develop novel PHY and MAC layer mechanisms for a functional and economically viable 5G access network in remote areas, compliant with 3GPP specifications. In this respect, a technical requirement of the 5G-RANGE access network was to support trusted or untrusted connectivity to public land mobile networks. For these reasons, the network layer was designed to include the components and the standard interfaces of a 5G core network, as defined by 3GPP [58], [59]. Moreover, the network layer design embraces the softwarization principles of 5G networking. In particular, it includes an ETSI NFV management and orchestration system that supports the flexible deployment of the constituent components of the 5G

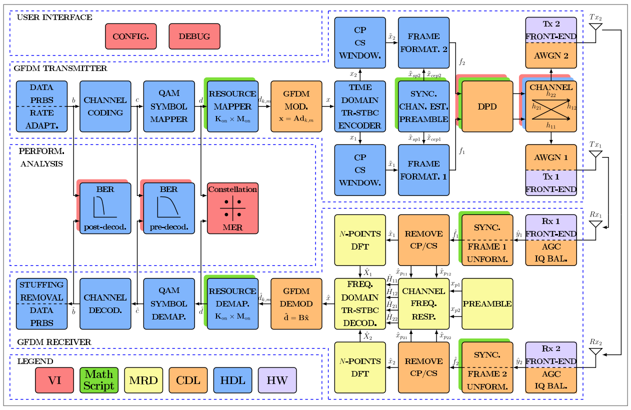


FIGURE 14. Block diagram of the prototype developed using the National Instruments LabView Communications platform.

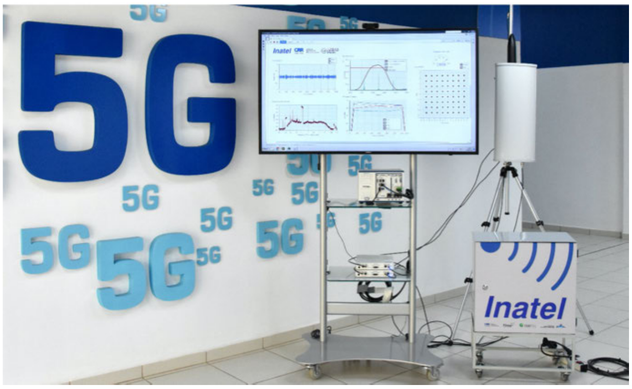


FIGURE 15. 5G-RANGE BS prototype implemented using National Instruments equipment.

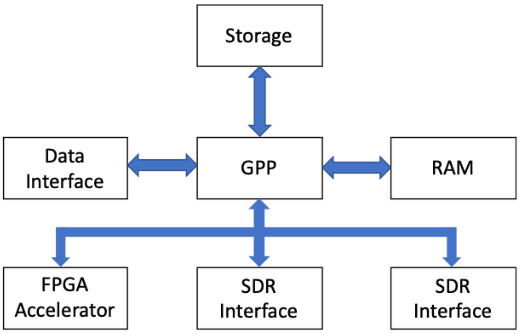


FIGURE 16. Architecture of the GPP based PoC platform.

core network, as well as of operator and third party services. Finally, it offers a cost-effective approach to complement the access network infrastructure resources using inexpensive resource-constrained platforms that can be made available on remote areas (e.g. onboarded on aerial or terrestrial vehicles, such as SUAVs, tractors, harvesters, etc.).

VII. PoC AND FIELD DEMONSTRATIONS

The 5G-RANGE network has been designed to provide reliable broadband Internet access and IoT services to support the use cases described in Sec. II. The 5G-RANGE project introduces a new operational mode for 5G, expanding its applicability for a true universal Internet access, with significant positive social and economic impacts in uncovered and underserved areas.

In order to demonstrate the full potential of the 5G-RANGE network, a Software-Defined Radio (SDR)-based PoC was built for real-time operation. The PoC consists of prototypes for the BS and for two UEs, which will be used to demonstrate the use cases described in Sec. II. Two different approaches were evaluated to construct the prototypes. The first one utilizes the National Instruments SDR platform composed by the LabView Communications software and Universal Software Radio Peripherals (USRPs) model 2954. LabView Communications is an interesting integration tool where blocks implemented in different programming languages can be combined in a single environment, providing solutions for fast prototyping and reliable debugging. USRP model 2954 supports 2 transmit and 2 receive RF ports capable of operating with signal bandwidths of up to 160 MHz. The supported frequency range is 10 MHz to 6 GHz. The devices are equipped with a Xilinx Kintex 7 Field Programmable Gate Array (FPGA) model XC7K410T, with more than 400 000 logic elements that can be used for implementing complex and computation intensive algorithms. A block diagram of the implementation as well as a picture of the BS prototype are provided by Fig. 14 and Fig. 15, respectively.

The second approach considered for the PoC development relies on SDR implemented mainly in software to be executed in a General Purpose Processor (GPP). This approach reduces the costs of the equipment and also allows evolution via firmware updates. This strategy brings more flexibility for the product development and the 5G-RANGE development team is implementing major PHY, MAC and NET blocks in software. The current generation of GPPs is able to provide more than 100 Mbps throughput and inexpensive SDR interfaces can generate and receive broadband wireless signals. The softwarization of the MAC and PHY components also helps transferring the technologies and solutions developed in the 5G-RANGE project to the market. Some PHY blocks demand a high level of parallelism to provide a high throughput, e.g., the Polar decoder and the MIMO demultiplexing. In both cases, a software implementation would be a bottleneck for the throughput. Therefore, the platform relies on an FPGA accelerator to perform timing critical tasks. An architecture overview and a picture of the SDR-based PoC prototype are provided by Fig. 16 and Fig. 17, respectively.

The PoC was used to analyze the system performance and compare the results with the KPIs presented in Table 1. Table 6 shows the parameters used for the field tests.

The BS was installed in Santa Rita do Sapucaí, Brazil and the measurements were performed in Campos do Jordão, Brazil, covering a maximum distance of 50.6 km in LOS condition. The maximum throughput achieved by the system was 102 Mbps. The ACLR has been measured in two points

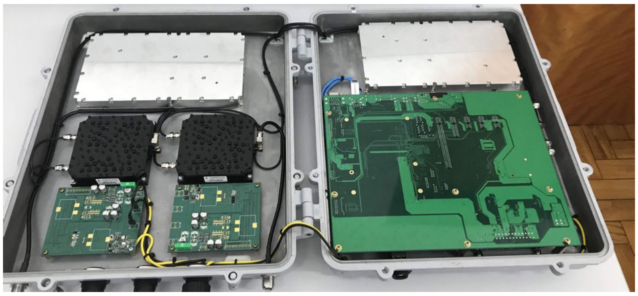


FIGURE 17. **Current development of the GPP based hardware platform.**

TABLE 6. **System parameters used for the test campaign.**

Parameters	Value
Transmit power	12 W + 12 W
Bandwidth	24 MHz
Center frequency	545 MHz
Number of transmit antennas	2
Number of receive antennas	2
MIMO scheme	STC
Channel code	Polar
Coding rate	2/3
Modulation order	256-QAM

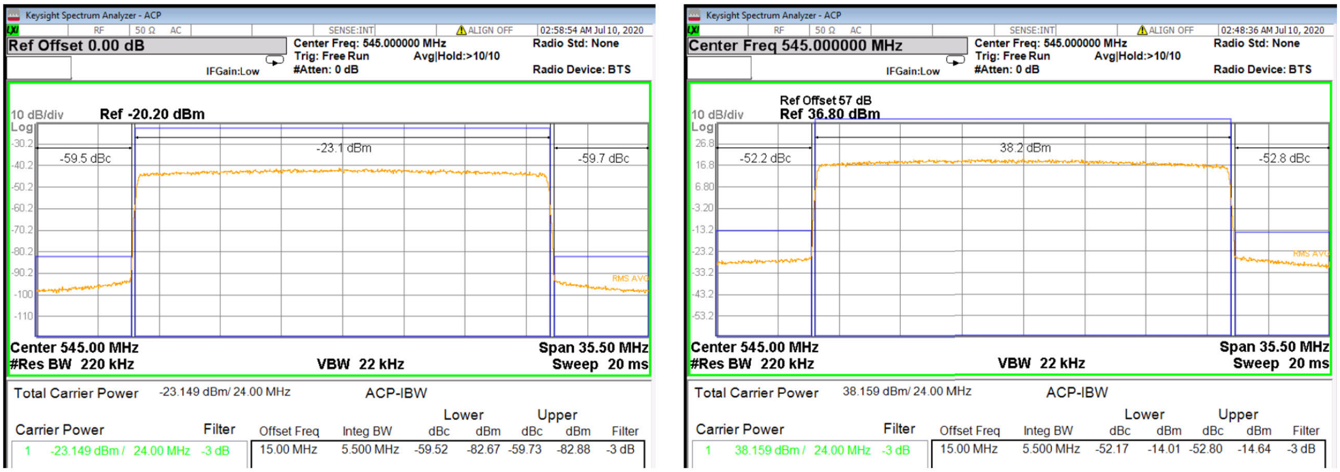
of the transmitter chain, as presented in Fig. 18. In both cases, no RF filter has been used. The ACLR before the power amplifier was 4.5 dB below the threshold defined in Table 1 for unlicensed spectrum operation. Due to resources limitations, an off-the-shelf power amplifier has been used. The non-linearities introduced by this device increased the ACLR. A Digital Pre-Distortion (DPD) [73] has been implemented to reduce the influence of the power amplifier in the OOBE. Fig. 18.b shows the ACLR after the power amplifier with the DPD, where one can observe that this parameter is 2.8 dB above the threshold defined in Table 1 for unlicensed operation and 7.2 dB below the threshold defined for licensed operation. Two different approaches are being considered for future works. The first one consists on designing a power amplifier that presents lower levels of non-linearities and the second one consists on introducing an automatic optimization algorithm that can adjust the coefficients of the DPD to meet a given criteria, based on a sample of the signal available at the output of the transmitter. Both solutions are expected to reduce the OOBE to the levels defined in Table 1.

The field demonstration of the PoC covers three of the use cases defined in Sec. II, namely Voice and Data Connectivity, Smart Farms and Wireless Backhaul. The 5G-RANGE BS was installed in a tower located in Santa Rita do Sapucaí, MG, Brazil and two UEs were installed in a rural property.

For the Voice Connection demonstration, one UE is able to perform a voice over IP call to the other UE without using the Internet connection, which means that the voice connection between the users will be handled by the 5G-RANGE core network. Fig. 19 depicts this use case.

For the Data Connectivity demonstration, the two 5G-RANGE UEs simultaneously access YouTube videos and Internet webpages. A satellite or optical link can be used as backhaul for the 5G-RANGE BS, as shown in Fig. 20

The smart farm and wireless backhaul use cases are demonstrated jointly. In this case, the 5G-RANGE UE 1 provides backhaul access for a Wi-Fi router which will distribute the Internet access link locally among several devices. 5G-RANGE UE 2 provides backhaul access to a LoRa gateway. IoT devices are deployed in the farm surroundings to measure soil humidity and pH, and air temperature. The sensors also collect data from cows. Actuators are used for a smart watering system and drones forward images to a server. Fig. 21 depicts the scenario for the smart farm and backhaul use cases. The integration of the 5G-RANGE with other technologies, such as LoRa and Sigfox, is an interesting



02:58:54 AM Jul 10, 2020
Ref Offset 0.00 dB
Center Freq: 545.000000 MHz
Trig: Free Run
Avg|Hold:>10/10
#Atten: 0 dB
Radio Std: None
Radio Device: BTS
Ref -20.20 dBm
Center 545.00 MHz
#Res BW 220 kHz
VBW 22 kHz
Span 35.50 MHz
Sweep 20 ms
Total Carrier Power -23.149 dBm/ 24.00 MHz
ACP-IBW

Carrier Power			Filter
1	-23.149 dBm /	24.00 MHz	-3 dB

		Lower		Upper		
Offset Freq	Integ BW	dBc	dBm	dBc	dBm	Filter
15.00 MHz	5.500 MHz	-59.52	-82.67	-59.73	-82.88	-3 dB

(a)

02:48:36 AM Jul 10, 2020
Center Freq 545.000000 MHz
Center Freq: 545.000000 MHz
Trig: Free Run
Avg|Hold:>10/10
#Atten: 0 dB
Radio Std: None
Radio Device: BTS
Ref Offset 57 dB
Ref 36.80 dBm
Center 545.00 MHz
#Res BW 220 kHz
VBW 22 kHz
Span 35.50 MHz
Sweep 20 ms
Total Carrier Power 38.159 dBm/ 24.00 MHz
ACP-IBW

Carrier Power			Filter
1	38.159 dBm /	24.00 MHz	-3 dB

		Lower		Upper		
Offset Freq	Integ BW	dBc	dBm	dBc	dBm	Filter
15.00 MHz	5.500 MHz	-52.17	-14.01	-52.80	-14.64	-3 dB

(b)

FIGURE 18. **ACLR measured during the field tests. (a) Before the power amplifier. (b) After the power amplifier with digital pre-distortion.**

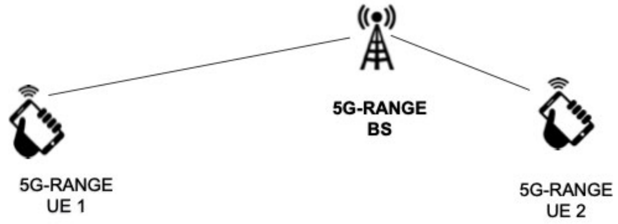


FIGURE 19. **Description of the voice connectivity use case.**

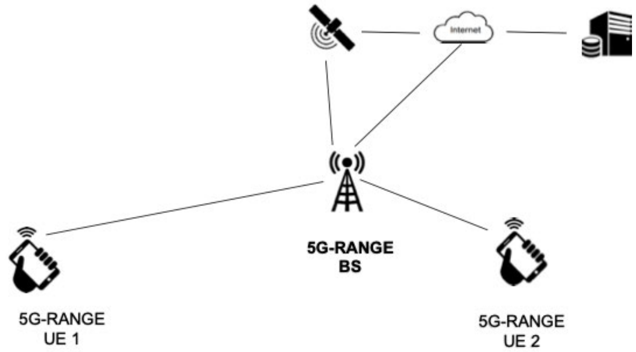


FIGURE 20. **Description of the data connectivity use case.**

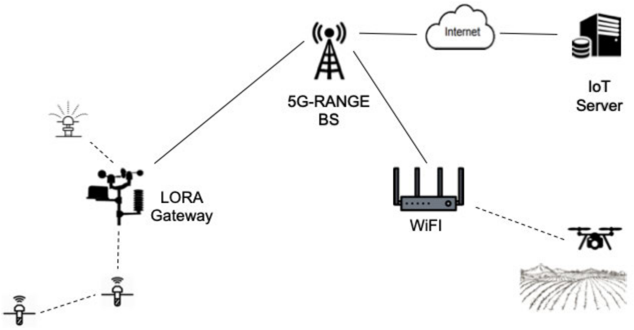


FIGURE 21. **Illustration of the Smart Farm and Wireless Backhaul use cases.**

solution for IoT applications in long-range scenarios. While the 5G-RANGE network can provide high data rates for long distance links, gateways can be used to concentrate the information from several devices, being responsible to send the data to the final destination through the 5G-RANGE network. The gateways can be installed in places where energy is available (tractors, farm buildings, remote stations) or the gateway can harvest energy using solar panels. The proposed integration can allow power-restricted devices to be deployed regions up to 50 km from the 5G-RANGE BS. Figure 21 also depicts this possibility.

VIII. BUSINESS MODELS FOR REMOTE AREAS NETWORKS

Considering that almost 50% of world's population (around 3.9 billion people) is not connected to the Internet [22], there are significant new market opportunities to be exploited by offering Internet services to the unconnected remote residents. This scenario calls for the development of new technologies and network operating models to better address challenges related to low density areas (typically in emerging markets) and to develop cost efficient solutions to offer Internet access [74].

A. CHALLENGES AND SHOW-STOPPERS

There are various reasons which hinder Internet adoption across a whole country or region. Each country or region has its own particular mix of challenges. For example, Europe has one of the most capillary mobile infrastructure in the world, leaving a very small percentage of the population unconnected, so this is not the priority in Europe. On the other hand, one of the key factors for Internet access and adoption across Latin America is extending the reach of mobile network infrastructure as a first step towards closing the digital divide. In the specific case of Brazil, there is still a big digital gap between Brazilian urban and rural areas. Urban areas have an Internet penetration of around 65% against 34% in the rural areas. In Europe urban areas have a penetration of around 81% vs 69% in rural areas. The reasons for these gaps include the following [75]:

- **High investment per covered inhabitant:** Rural population tends to be spread across a larger area and grouped in low-density towns, which makes reaching each single dweller a harder enterprise. Furthermore, rural topography can present additional challenges to deploy backhaul to reach remote towns, making rural connectivity a high CAPEX per inhabitant activity.
- **Operational complexity and cost:** Operations & Maintenance (O&M) is one of the main Operational Expenditure (OPEX) costs for network operators. Any malfunction which requires site visit and repair are much more expensive for remote and harder to reach areas. Furthermore, a lack of stable energy supply gives rise to the need to strengthen the electric grid, thus increasing O&M costs.
- **Lack of accurate data:** Outdated census and fast changing migratory movements in rural areas make it hard to correctly and accurately quantify the rural opportunity by towns.
- **Revenue uncertainty:** Most industry data is based on urban deployments and there is very limited rural historical data. This makes it harder to extrapolate projections in rural areas, both in the potential Average Revenue per Unit (ARPU) to be achieved and the level of adoption to be expected across rural regions.
- **Network Operator investment prioritization:** The combination of a high CAPEX intensive business, fierce competitive dynamic between network operators in the urban fight, a higher investment per covered inhabitant in rural areas and higher operational costs and the uncertainty of the potential rural revenues to be achieved, create a situation in which a profit-minded network operator

will not be able to prioritize rural deployments above other more profitable and risk-adjusted business cases.

- **Regulatory framework:** The fast-pace of digital transformation present a challenge for regulatory bodies who cannot analyse and adapt to new technology in a timely manner. A more visionary regulatory entity could help in exploring new business models to bring connectivity in a different way.

To overcome these identified show-stoppers and have a sustainable business model, it is important to design the right mechanisms with the right incentives to foster massive adoption. In order to motivate the investment in broadband coverage in unconnected areas it is critical that the public policies and regulatory framework minimize the barriers and the regulatory uncertainty for players willing to enter this space. Specifically, regulation should: (i) be open to innovative business models and types of services; (ii) bring greater regulatory flexibility; (iii) be technologically neutral to create optimal combination of spectrum and solutions; (iv) explore softer Quality-of-Service (QoS) requirements in rural areas; and (v) provide investment incentives, access goals and other options over fees, sanctions and/or penalties.

B. MARKET OPPORTUNITIES

In order to evaluate the market opportunity related to connecting the unconnected in a country, knowledge about how the population is geographically distributed and, which parts of that population have access to Mobile Broadband (MBB) services and which parts do not must be acquired [75]:

Using Brazil as the case study, an intelligence algorithm has been generated around the main inputs required to make the segmentation and sizing of the opportunity for Brazil, including population, telecommunication infrastructure and overall coverage data. The Total Addressable Market (TAM) in Brazil is between 10 and 20 million unconnected people for any given Mobile Network Operator (MNO), most of which are Greenfield (meaning there is no Second Generation of Mobile Network (2G) in that given area) and a small amount is Overlay (meaning that there is 2G in that area). These unconnected people live in a total of around 34000 settlements and sets the scene for new business opportunities in rural areas [76].

C. BUSINESS MODELS FOR RURAL AREAS NETWORKS

Once the TAM has been estimated, next step towards building the business model is to estimate the best way to tackle the deployment of new connectivity where required. In this context, an alternative deployment/business models to connect the unconnected in Brazil has been considered, which also can be extrapolated to other countries, bringing multiple stakeholders to find a concerted and holistic approach:

- **Rural Mobile Infrastructure Operator (RMIO):** Entity which decouples the MNO from a potential local infrastructure company that deploys in a certain delimitation and closes a revenue share deal with one or various MNOs. This figure has already been implemented in Peru and can be extrapolated to Brazil and other countries [75]. From an operational business model perspective, this is an attractive setup for both sides. On the RMIO side, it can deploy non-competing and value-added infrastructure in a rural area, with the assurance that it can then force MNOs to partner and close a commercial agreement to capture its potential clients in the area. On the MNO side, it allows to focus CAPEX on high-density, urban areas where competition is fierce and,, at the same time, expand user adoption in rural areas in partnership with the RMIO with limited additional investment and making use of its licensed spectrum which was not being capitalized in the RMIO unserved area to date. An overview of this business model and the role of the RMIO in the value chain is presented in Figure 22.

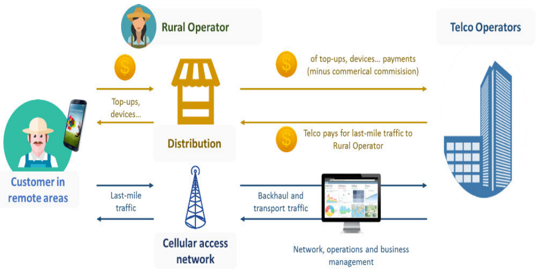


FIGURE 22. **Rural Operator Role in the Value Chain.**

- **Network Sharing:** Various forms of network sharing should be considered, including agreements across companies with infrastructure ownership and MNOs or Mobile Virtual Network Operators (MVNOs), etc. Two main forms of network sharing should be highlighted:
  - **Passive sharing:** MNOs share the physical components of the cell site, installing multiple antennas on a single tower to optimize costs.
  - **Active sharing:** MNOs also share more advanced components of their infrastructure, most commonly their Radio Access Network (RAN), less commonly their transport and backhaul network and rarely sharing their Core network.

The 5G-RANGE project tackles the unconnected opportunity assuming the role of an MNO with the help of the RMIO (as shown in Figure 22), which can be applied to all use cases defined in the Sec. II. This brings flexibility to the business model and can help the solution to be widely adopted. Advantages of this approach are the distribution of incurred costs between MNO and RMIO and a fair split of the value generated by the TAM opportunity, as shown in [76], which makes the model attractive and scalable from the perspective of both operators.

It is worth noticing that, besides the adopted business model approach, there are some critical parameters to determine the dynamics of service adoption and revenue generation. One of them is the connectivity penetration, defined as the percentage of the population that would eventually access MBB services. As there is yet no ecosystem of devices compatible with 5G-RANGE, today the penetration would be somewhere around zero, but it is expected that the deployment of the 5G-RANGE networks should come together with the creation of compatible devices, increasing 5G-RANGE penetration and reducing network costs year over year. Also, the connectivity penetration can be accelerated by pushing the 5G-RANGE solution as part of the 3GPP specification, which is a primary goal of the 5G-RANGE project. 5G-RANGE CPEs can also be integrated with other technologies, allowing for off-the-shelf devices and smartphones to be promptly used, which severely reduces the initial cost of the network deployment.

IX. CONCLUSION

5G for remote areas is an important scenario for B5G networks, with huge social and economic impacts. The three operation modes being defined by 3GPP are not originally aimed to address the requirements for remote areas networks. The 5G-RANGE project has conceived a new operation mode for B5G networks based on the most recent technologies, but tailoring the parameters to support long-range coverage with low OOBE and high robustness against frequency selective channels. GFDM, a more flexible multi-carrier filtered waveform, has been selected as air-interface due to its good frequency localization and possibility to cover conventional waveforms as corner cases. Polar code has been selected as the channel code for both data and control planes because of its robustness and good performance compared with LDPC codes. 5G-RANGE also has innovated the MAC layer by adding the cognitive cycle, which uses the low OOBE provided by the waveform to exploit TVWS in an opportunistic approach. The network layer provides connectivity to a plethora of services and also connects the 5G-RANGE system to the 5G Core Network through 3GPP and non-3GPP interfaces. The entire system has been implemented in a PoC capable of achieving 100 Mbps at 50 km from the BS. The developed BS and UEs prototypes were used to demonstrate the full potential of a remote area network, which can be economically exploited by the business models described in this paper. The results achieved by the 5G-RANGE project show that the technology is ready to provide a cost-effective and reliable remote area network using the main techniques developed for 5G networks, but tailored for this important scenario. B5G can be the final answer to close the connectivity gap between urban and rural area, bringing a true universal Internet coverage everywhere for everyone.

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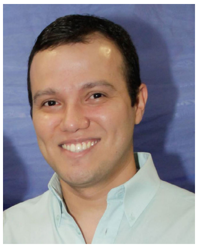
LUCIANO LEONEL MENDES (Member, IEEE) received the Ph.D. degree in electrical engineering from the State University of Campinas, Brazil, in 2007. Since 2001, he has been a Professor with the National Institute of Telecommunications (Inatel), Brazil, where he acts as a Research Coordinator of the Radiocommunications Reference Center. He is currently the Research Coordinator of the 5G-Brasil project. His research interest includes physical layer for future mobile networks.

CARLOS SALLÉ MORENO has a background in industrial engineering (Universidad Politécnica de Madrid and CentraleSupélec). He worked with Telefónica for four years with special focus on rural connectivity, innovation and data science. He is currently working with Accenture in the applied intelligence area implementing data science and AI projects

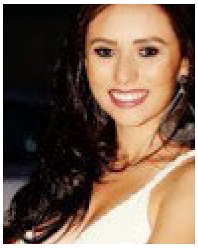
MARIA VALÉRIA MARQUEZINI (Member, IEEE) received the D.Sc. degree in physics from the State University of Campinas (UNICAMP), Brazil, in 1995. From 1995 to 1997, she worked as a Postdoctoral Researcher with the Lawrence Berkeley National Laboratory, Materials Science Division. From 1997 to 1999, she worked as an Associate Researcher with the Physics Institute, UNICAMP, conducting research activities in the field of electronic processes in semiconductors. Since 2000, she has been working in the research department of Ericsson in Brazil and has been involved in many research projects in the telecommunications domain.



ANDRÉ MENDES CAVALCANTE (Member, IEEE) received the Ph.D. degree in electrical engineering from the Federal University of Pará (UFPA), Brazil, in 2007. From 2007 to 2016, he was the Coworker with the Nokia Institute of Technology (INDT), Brazil, where he was involved in several research and development projects related to wireless communications. He is currently a Senior Researcher with the Ericsson Research, Brazil. His research interest includes mobile transport network for future wireless communication systems.

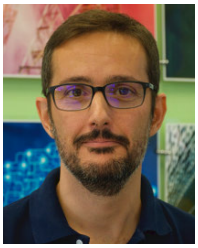
PETER NEUHAUS (Graduate Student Member) received the B.Sc. degree and the M.Sc. degree (Hons.) in electrical engineering, information technology, and computer engineering from RWTH Aachen University, Germany, in 2014 and 2017, respectively. He is currently pursuing the Ph.D. degree with the Technische Universität Dresden. In 2017, he joined the Vodafone Chair Mobile Communications Systems, Technische Universität Dresden. His research interests include signal processing and communications.

JORGE SEKI received the B.Sc. and M.Sc. degrees in electrical engineering from the Polytechnic School, University of Sao Paulo, Brazil, in 1990 and 1995, respectively. He worked with Microelectronics research, and the Industrial Automation and Network Engineering. Since 2002, he has been working with the CPQD Foundation in Telecommunication Research and Development.



NATHÁLIA FIGUEIREDO TINOCO ANICETO received the degree in telecommunication engineering from the University of São João del Rei (UFSJ), in 2017, and the master's degree. She is currently working as a Researcher with CPQD. She has published some scientific articles in conferences and journals. Her research interests include mobile communications and 4G/5G networks.

HEIKKI KARVONEN (Member, IEEE) received the Dr. Tech. degree in telecommunications from the University of Oulu, Finland, in 2015. He is currently working as a Researcher and a Project Manager with the Center for Wireless Communications (CWC), University of Oulu. He has gained experience of several national and international research projects carried out at the CWC from 2003 to 2020. He has focused on cellular communication techniques (3G-5G) and the Internet of Things (IoT) communication research.



IVAN VIDAL (Member, IEEE) received the degree in telecommunication engineering from the University of Vigo, in 2001, and the Ph.D. degree in telematics engineering from the University Carlos III of Madrid–Leganes, in 2008. He is currently working as a Visiting Professor with the Universidad Carlos III de Madrid–Leganes. He has been involved in several international and national research projects, including the EU IST MUSE, Trilogy, the H2020 5GINFIRE, MEDIANET, and 5GCITY. He has published more than 50 scientific articles in several conferences and international journals, lately in the areas of UAVs and network functions virtualization. His research interests include unmanned aerial vehicles (UAVs), 5G networks, multimedia networking, and network security.

FRANCISCO VALERA received the degree in telecommunication engineering from the Technical University of Madrid (UPM), in 1998, and the Ph.D. degree in telecommunications from the Universidad Carlos III de Madrid–Leganes (UC3M), in 2002. He is currently a Tenured Associate Professor and the Head of the Department of Telematics Engineering, UC3M. He has published over 80 articles in the field of advanced communications in magazines and conferences.

PRISCILA AMERICA SOLÍS MENDEZ BARRETO received the Ph.D. degree in electrical engineering from the University of Brasilia (DF), Brazil, in 2007. She is currently an Associate Professor with the Department of Computer Science (CIC), University of Brasília. Her research interests include computer networks mainly in traffic analysis, performance evaluation, protocols, routing optimization, and mobile computing and 5G.

MARCOS FAGUNDES CAETANO (Member, IEEE) received the B.S. degree from the Federal University of Santa Catarina, in 2005, and the M.S. and Ph.D. degrees from the University of Brasilia, in 2008 and 2017, respectively, all in computer science. He has experience in the area with emphasis on computer systems. He is currently a Professor with the Department of Computer Science, University of Brasilia. His research interests include mobile computing, computer networks, VANET, the IoT, and multimedia networks.

WHEBERTH DAMASCENA DIAS received the degree in electrical engineering from Inatel, Brazil, in 2006, where he is currently pursuing the master's degree. He also holds a position as a Research and Development Engineer of the Radiocommunications Reference Center, Inatel.

GERHARD FETTWEIS received the Ph.D. degree from RWTH Aachen University under the supervision of H. Meyr. After one year at IBM Research, San Jose, he moved to TCSI, Berkeley. Since 1994, he has been a Vodafone Chair Professor with TU Dresden. Since 2018, he heads the Barkhausen Institute. He researches wireless transmission and chip design, coordinates two DFG centers (cfaed and HAEC), the 5GLab Germany, has spun-out sixteen startups, and is also a member of two German academies: (Sciences) "Leopoldina", (Engineering) "acatech".

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