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Building Upon NB-IoT Networks: A Roadmap Towards 5G New Radio Networks

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ABSTRACT Narrowband Internet of Things (NB-IoT) is a type of low-power wide-area (LPWA) technology standardized by the 3rd-Generation Partnership Project (3GPP) and based on long-term evolution (LTE) functionalities. NB-IoT has attracted significant interest from the research community due to its support for massive machine-type communication (mMTC) and various IoT use cases that have stringent specifications in terms of connectivity, energy efficiency, reachability, reliability, and latency. However, as the capacity requirements for different IoT use cases continue to grow, the various functionalities of the LTE evolved packet core (EPC) system may become overladen and inevitably suboptimal. Several research efforts are ongoing to meet these challenges; consequently, we present an overview of these efforts, mainly focusing on the Open System Interconnection (OSI) layer of the NB-IoT framework. We present an optimized architecture of the LTE EPC functionalities, as well as further discussion about the 3GPP NB-IoT standardization and its releases. Furthermore, the possible 5G architectural design for NB-IoT integration, the enabling technologies required for 5G NB-IoT, the 5G NR coexistence with NB-IoT, and the potential architectural deployment schemes of NB-IoT with cellular networks are introduced. In this article, a description of cloud-assisted relay with backscatter communication, a comprehensive review of the technical performance properties and channel communication characteristics from the perspective of the physical (PHY) and medium-access control (MAC) layer of NB-IoT, with a focus on 5G, are presented. The different limitations associated with simulating these systems are also discussed. The enabling market for NB-IoT, the benefits for a few use cases, and possible critical challenges related to their deployment are also included. Finally, present challenges and open research directions on the PHY and MAC properties, as well as the strengths, weaknesses, opportunities, and threats (SWOT) analysis of NB-IoT, are presented to foster the prospective research activities.

INDEX TERMS Backscatter communication, cloud RAN, enabling market, long-term evolution, machine-type communication, narrowband Internet of Things, 5G new radio coexistence, PHY, MAC, SWOT analysis.

I. INTRODUCTION

The Narrowband Internet of Things (NB-IoT) is a release 13 3GPP technology built on the platform of long-term evolution (LTE) functionalities. NB-IoT will continue to coexist and operate seamlessly with new 5G networks, thus supporting LTE-IoT deployment scenarios. The existing 4G LTE networks employed to test the implementation of different NB-IoT connectivity and applications [1] remain an ongoing effort, particularly as the capabilities of various existing low-power wide-area network (LPWAN) technologies continue to grow [2]. Despite the attempt to optimize current LTE broadband systems, they remain unsuitable for many machine-type communication (MTC) applications. MTC plays an essential role in the core of NB-IoT connectivity between devices and the cloud. 5G networks are expected to create a horizontal transformation approach [3] to drive massive numbers of NB-IoT devices and applications by expanding the operation of the cellular-IoT. 5G data infrastructure plays a vital role in LPWA-based IoT devices

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that need strong security, widespread availability, ultra-low latency, ultra-low power consumption, wide coverage area, low device cost and high reliability [4] for streamlining and improving a variety of services and industries. According to the International Data Corporation (IDC) survey, billions of dollars are spent by companies to drive 5G services requiring ubiquitous connectivity, including mobile, nomadic, and stationary, to the tens of billions of devices, objects, and machines [5]. The connected devices in return, generate immense economic value across the world. To make NB-IoT a core component in achieving this dream, a roadmap for NB-IoT towards 5G networks is the focus of the present article.

Considering the differences between this survey and other articles that have emerged to examine NB-IoT connectivity and limitations, this is the first survey paper detailing practical features of NB-IoT coexistence with 5G new radio (5G NR), and open research challenges that may hinder the conduct of NB-IoT carriers within the NR network. For instance, the author of [6] surveyed a comparative study of media access control (MAC) layer protocols of long-range and short-range LPWA technologies to gain insight, and a reference study of the features, constraints, behavior and open research issues of IoT applications. The author in [7] analyses the design decisions' impact on the design goal requirements for the suitability of given IoT applications. The author outlines seventeen use cases across twelve domains to prioritize each design goal's significance to those applications. The analysis of technical terms based on the physical and MAC layers of LPWA technologies was surveyed in [8]. In [9], a physical layer design for DL scheduling and resource allocation in NB-IoT was presented. The highlight of [10] documents the draft reforms made of NB-IoT standardization, with the comprehensive study process from the perspective of physical and MAC layers. The surveys mentioned above have presented a brief knowledge of the NB-IoT network relationship with 5G NR networks. However, the survey mentioned provides immense guidance for our studies.

In comparison to current studies, the contributions of this paper are as follows:

- A comprehensive flowchart of the 5G-IoT class of connectivity is presented and also, a definite difference between the NB-IoT protocol stack and the OSI reference model concerning optimized LTE NB-IoT architecture is discussed, as well as the popular features of the 3GPP releases from 13 to 17.
- We list specific features between the 5G NR and NB-IoT numerologies to promote the coexistence of 5G NR and NB-IoT, and also, describe the limitations of the technical performance properties of 5G NB-IoT networks, as well as the current solutions proffered for the PHY/MAC channel communications challenges.
- We describe the possibility of architectural design for cloud-assisted relay with ambient backscatter communication for the 5G NB-IoT network.
- We discuss the market analysis of NB-IoT, the benefits for a few use cases, and possible critical challenges related to their deployment.
- The research challenges and discussion of 5G NB-IoT networks for planning future research works, as well as a SWOT analysis of NB-IoT, are presented.

This paper is structured as follows: Section II presents the background to the 5G-IoT class of connectivity. Section III discusses the overview of NB-IoT, highlights the technical differences between NB-IoT and other LPWA technologies, and summarizes the design objectives and benefits of NB-IoT. Section IV presents the OSI layer framework and optimized LTE-NB-IoT architecture design and the 3GPP standardization and releases for NB-IoT. Section V details the 5G architecture design for NB-IoT integration, and the enabling technology needed for the 5G NB-IoT network. Section VI describes the possibility of architectural design of cloud-assisted relay with ambient backscatter communication for 5G NB-IoT. Section VII highlights the 5G NR coexistence with NB-IoT, the similarity between the NR and NB-IoT, and the achievable architecture deployment schemes for asynchronous and synchronous network distribution structures. Section VIII discusses the technical performance properties of NB-IoT, detailing the PHY/MAC challenges concerning various channel parameters and possible solutions. Section IX describes the enabling market analysis for NB-IoT, applications and use cases with some potential problems affecting their deployment. Section X discusses the open research challenges and provides a SWOT analysis of NB-IoT in 5G NR carrier networks and finally, section XI concludes the survey.

II. BACKGROUND TO 5G-IOT CLASS OF CONNECTIVITY

The 5G networks utilize intelligent architectures of radio access technology (RAT), dynamic by nature, coherent, and flexible over multiple advanced technologies that can support NB-IoT and a wide variety of IoT applications. According to the new 3GPP releases 16 and 17, the adaptation of 5G-IoT services can create a link with high performance and low complexity to virtually everything around us [11]. The 5G-IoT can improve the spectral efficiency and data rate of NB-IoT, and thus promote the total addressable market of NB-IoT devices and 3GPP solutions for IoT use cases. In Figure 1, 5G-IoT has three classes of connectivity, namely; wired, wireless, and satellite [12], but wireless technologies will be reviewed. The 5G-IoT wireless technologies can be classified into two groups based on transmission distance as short-range MTC wireless technologies (e.g. WHAN, Wi-Fi, and WPAN, examples such as Bluetooth, Mi-Wi, ANT, 6lowpan, ZigBee, and Z-wave) [13] and long-range MTC wireless technologies (e.g. low-power, wide-area networks (LPWAN)), and finally, the MTC services [14].

Considering the perspective of frequency spectrum licensing, LPWAN can be categorized into two classes, namely; the non-3GPP standards (unlicensed spectrum) and the 3GPP standards (licensed spectrum), [14]. The first category

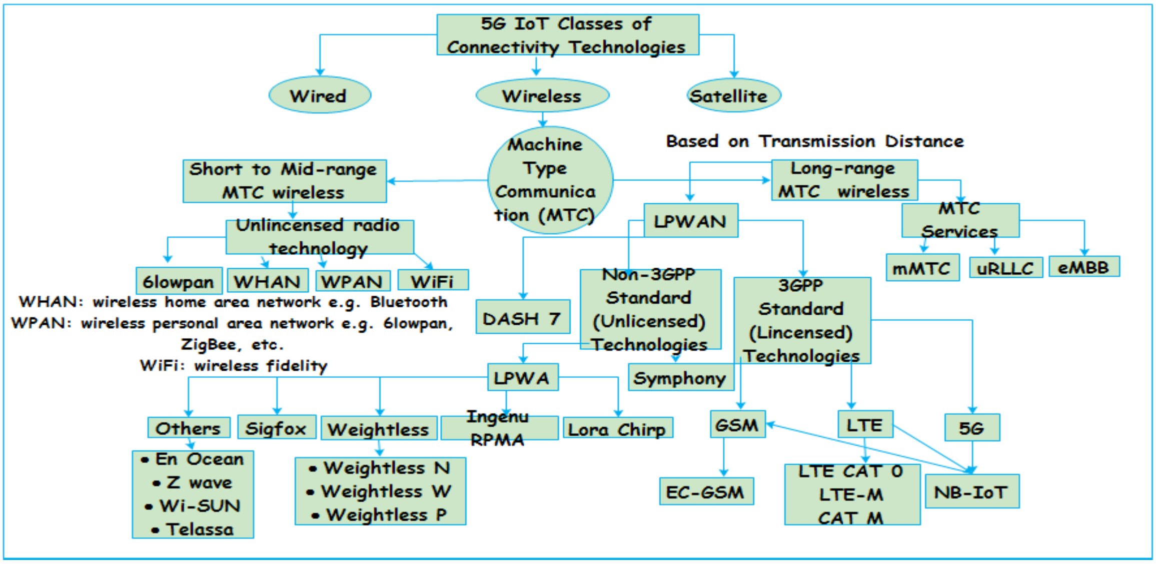


FIGURE 1. Classes of 5G-IoT connectivity Based on Transmission Distance.

consists of LPWA technologies such as Sigfox LoRa, Weightless, Ingenu RPMA, Z-wave [15], etc. that are of custom and non-standard implementation. For instance, LoRa and Sigfox operate in the sub-Gigahertz unlicensed spectrum while RPMA operates in 2.4 GHz industrial, scientific and medical (ISM) bands. More importantly, this category has limited channel access due to the spectrum shared between different technologies. The transmission time has a limited duty cycle and a listen-before-talk or frequency-hopping scheme implemented to avoid interference with other coexisting systems. The second category is based on 2G/3G cellular technologies (such as the GSM, CDMA, WCDMA), LTE, and evolves LTE technology that supports different classes of terminals [16]. The standards for the second category (licensed spectrum) were developed by the 3GPP and 3GPP2 [10]. Unlike the unlicensed spectrum, the licensed spectrum does not suffer from the duty cycle and uncontrollable interference [17]. In general, MTC has limited power at the device side while the network can still benefit from the increased downlink link-budget due to the high base station (BS) transmitting power. Based on the modification, specific demands [18] and features of MTC services related to 3GPP set objectives of release 13, three (3) kinds of narrowband air interfaces were defined, namely, extended-coverage GSM internet of things (EC-GSM-IoT), enhanced machine-type communication (eMTC) known as LTE-M (LTE-Cat M1) or Cat M and the new NB-IoT technology.

The EC-GSM-IoT is a high-potential, long-range, low-energy, and low-complexity technology-based eGPRS system. The eMTC supports applications with higher data rate and mobility requirements designed for LTE enhancement, for the implementation of MTC and IoT. As regards the new NB-IoT technology, on the other hand, the focus of this article is intended for intelligent low-data rate applications for data perception and acquisition.

The MTC service offers an optimized 3GPP network support to connected devices and services to the potential 5G-IoT as specified in Rel. 14 [19]. The 5G-IoT, is expected to connect more than 70 use cases cutting across a range of new services and markets from IoT to vehicular communications, applications, and control, industrial automation, tactile internet, drone control systems, remote maintenance, and monitoring systems [20], theft prevention and recovery, as well as smart cities [21], smart buildings and surveillance [22], intelligent health systems, smart metering [23], smart grid [24], smart parking, smart lighting, shared bicycle, connected cow [15], [25], and lots of other use cases. The use cases have inspired research issues related to the capacity and services of the deployed 5G communication systems.

The 5G-MTC services are: Enhanced mobile broadband (eMBB), Ultra-reliable and low-latency communication (uRLLC), and lastly, massive machine type communication (mMTC). The services offer enhanced localization support, multicast, mobility, high data rate, positioning update, new user equipment output class necessary for system throughput, and link adaptation to 5G NB-IoT and cellular IoT.

To further bolster this point, two-step strategies are adopted by 3GPP to puzzle-out the technological challenges from the MTC services. The transition strategy is the first step taken.

The first strategy optimizes the existing network and technologies to offer MTC services [26]. The second strategy, termed a long-term strategy, provides support to the rising large-scale MTC services based on the introduced new air interface of NB-IoT, and for maintaining core competitiveness to non-3GPP LPWA technology [27].

The diverse NB-IoT software and hardware solutions deployed from different vendors such as the Skyworks [28], Media Tek [29] Qualcomm [30], Sierra wireless [31], Neul (Huawei) [32], Intel [33] and so on, have made it possible for the Telecom operators across the globe to carry out

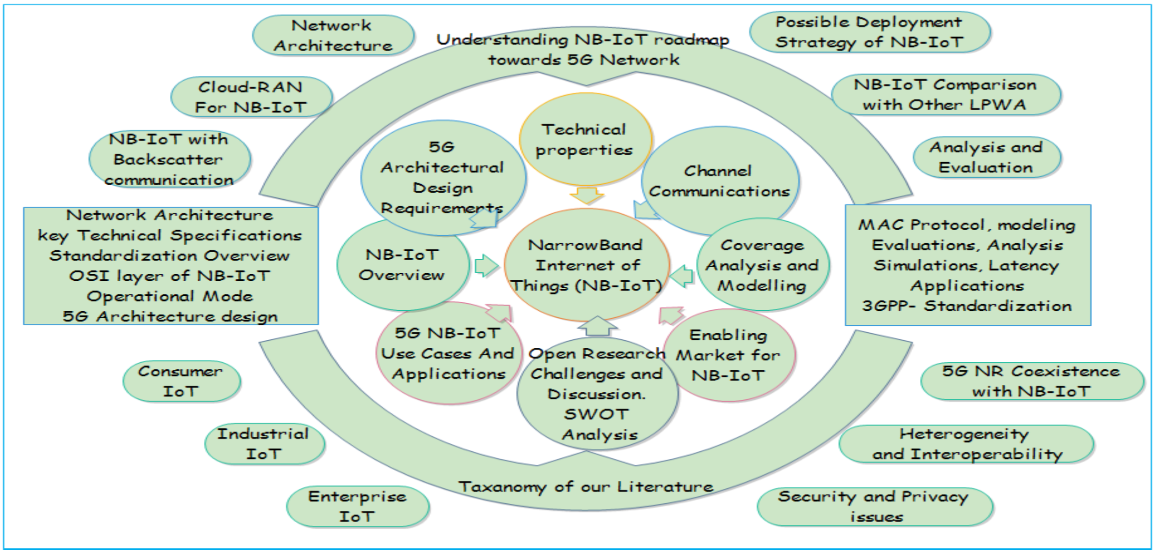


FIGURE 2. Brief Taxonomy of Literature.

practical feasibility studies of different NB-IoT use cases with real-life trials such as the smart city in Las Vegas, USA [34], smart metering and tracking in Brazil [35], NB-IoT at sea in Norway [36], [37] and so on, to mention a few. The products implemented from different vendors speed up the adopted NB-IoT technology. Numerous studies detailing the architecture design and OSI layer, coverage enhancement mechanism, theories, modeling, security challenges, channel estimation and limitations are highlighted in this survey. Figure 2 presents the taxonomy of the literature studies. The study classifies nine main sections, each section with a sub-branch as mentioned above.

III. AN OVERVIEW OF NARROWBAND INTERNET OF THINGS (NB-IoT)

NB-IoT is an open 3GPP standard optimized for MTC traffic to lower the energy consumption of IoT use cases. The narrowband radio technology was designed specifically for LPWA applications to support a low data rate, very low power consumption, scalability, and long-range coverage of cellular data. It promotes the development and implementation of intelligent IoT. NB-IoT can be integrated into the 5G new radio (5G-NR) networks, to bolster the ultralow-end IoT applications, including the intelligent meters, remote sensors and smart health systems [15].

NB-IoT (also known as LTE-Cat-NB1) provides simplification and optimization of enterprise-grade technical specifications that reduce the radio overhead and deliver IP and non-IP data [38], being the practical choice for carriers, device manufacturers and enterprise users [39]. The NB-IoT integrates into the existing network and promotes optimal coexistence by occupying a physical resource block of 180kHz for both uplink (UL) and downlink (DL) operations or by replacing one GSM carrier of 200kHz without compromising the host network's performance. According to [38], NB-IoT supports cell reselection in idle state but does not aid hand-over services in the connected state. Also, due to the features of employing power-saving mode (PSM), NB-IoT lacks provision for QoS. Table 1 tabulates the key technical specifications (KTS) of NB-IoT in comparison with other LPWA technologies.

The summary of the design objectives and benefits of NB-IoT [17], [40]–[42] is as follows;

- The complexity of the transceiver is lower.
- Energy consumption is lower.
- Radio-chirp is lower.
- It has a maximum-coupling loss of 164 dB for coverage improvement.
- It should provide multi Physical Resource Block (PRB)/Carrier support.
- It adopts a HARQ process of adaptive and asynchronous for both UL and DL.
- FDD only and half-duplex User Equipment (UE)
- Employs 180kHz (1PRB) for narrowband physical DL channel.
- Uses 3.75kHz random-access preambles (RAP).
- Can adopt a single tone (15 kHz/3.75 kHz) or multi-tone (n*15 kHz, n = (3,6,12)).
- Uses 680 bits and 1000 bits of the maximum transport block size (TBS) for DL and UL.
- NB-IoT offers support for up to 10s for UEs using eDRX when connected, but uses 3hrs for UEs in idle state.
- Has a power spectral boosting of 6dB relative to the LTE system, and the multiple repetitions method can aid in improving the received signal quality.
- NB-IoT provides 20dB improvement in coverage relative to LTE.
- An NB-IoT carrier can support the transmission of short messages to the network from more than a hundred thousand devices. Additional carriers to the system can scale the network connections to millions of devices.

TABLE 1. [7], [15], [39], [43] The key technical specifications of NB-IoT in comparison with other LPWA Technologies

KTS	Sigfox	LoRa	NB-IoT	eMTC	EC-GSM-IoT
Technology	Proprietary	Proprietary	Open LTE	Open LTE	Open
Coverage	160dB	157dB	20dB	15dB	20dB and 14dB
Spectrum	Unlicensed	Unlicensed	Licensed (LTE/any)	Licensed (LTE band)	Licensed GSM band
Duty cycle restriction	Yes (typically 1%)	Yes (typically 1%)	No	No	No
Downlink data rate	0.1 kbps	0.3-50 kbps	0.5- 200kbps	1MHz	74kbps
Uplink data rate	0.1 kbps	0.3-50 kbps	0.3-180kbps	1MHz	240 kbps
Battery life (200b/day)	10+ yrs	10+ yrs	15+ yrs	+10 yrs	+10 yrs
Module cost	< $10 (2016)	< $10 (2016)	$ 7 (2017) to $ 2 (2020)	< $ 10	$ 7
Security	KGME, MAC verification, Sequence	AES COM 128	NSA, AES 256	AES 256	AES 256
Frequency band	EU: 868MHz US: 90 MHz	EU: 868MHz US:433/ 915 MHz. AS: 430MHz	In-band, Guard & Stand-alone LTE Frequency	In-band LTE Frequency	GSM Frequency
Channel bandwidth	100 Hz	250 kHz and 2.16 MHz	180kHz (200kHz carrier)	1.08MHz (1.4MHz carrier bandwidth)	2.4MHz
3GPP release	Not supported	Not supported	13	12	13
Duplex mode	Half-duplex	Half-duplex	Half-duplex FDD only	Full and half duplex FDD/TDD	Half-duplex FDD only
MCL	3dB	3dB	+164dB	+155.7dB	+164dB & 154dB
Rx antenna	Single	Single Rx	Support single Rx	Support single Rx	Support single Rx
Max. transmit power	14dBm/ 22dBm	14dBm/27dBm	20dBm or 23dBm	20dBm or 23dBm	33dBm or 23dBm
PSM	Deployment driven	3 classes of device operation	PSM, eDRX	PSM, eDRX	PSM, eDRX
Reliability	Low reliable	Low reliability	Highly reliable	Reliable	Reliable
Interference/distance	High	Very high	Low	Low	Low
Network congestion under high load	High packet loss	Very high packet loss as throughput degrades	Low	Low	Low
Base station capacity	Millions of devices/ access point	1,000,000 devices	52,547	80,000	50,000
Supports	Sigfox alliance	LoRa alliance	By over 30 of world's largest operators such as AT&T, China-Unicom, etc	By over 30 of world's largest operators such as AT&T, China-Unicom, etc.	By over 30 of world's largest operators such as AT&T, China-Unicom, etc.
Latency	< 10s	< 10s	< 10s for 164dB	~5s for 155dB	< 10s
Mobility	40km/h	40km/h	Cell selection, re-selection only (80km/h) (Normadic)	Legacy support (120km/h)	GSM support ()
Coexistence	ISM band	ISM band	GSM standalone, LTE in-band, LTE guard band, 5G NR	LTE in band	LTE in band
Reduced complexity	High	High	Ultra-low cost (˜1$)	Similar to EGPRS modem cost	Similar to EGPRS modem cost
Standardization	A collaboration of ETSI and Sigfox alliance	LoRa alliance	3GPP	3GPP	3GPP
Topology	Star	Star of Star	Star	star	Star
Modulation	DBPSK (UL) GFSK (DL)	Chirp spread spectrum (CSS) CSS	QPSK/BPSK (DL) GFSK (UL)	OFDMA SC-FDMA	GMSK
Localization	Yes (RSSI))	Yes (TDOA)	Not (under specification)	No (under specification)	No (under specification)
Handover	No centralized base-station for end-devices.	No centralized bas -station for end-devices.	Centralized base-station provided for all devices	Centralized base-station provided for all devices	Centralized base-station provided for all devices
Allow private network	No	Yes	No	No	No
Adaptive data rate	No	Yes	No	No	No
Max. payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	Network Deployment-driven	Network Deployment-driven	Network Deployment-driven.
Max. Message/day	140 (UL), 4 (DL)	Unlimited	Unlimited	Unlimited	Unlimited
Bi-directional	Yes	Yes	Yes	Yes	Yes
Phonetic Ability	Not supported	Not supported	Not supported	Limited capacity / Weaker than FDD for FDD/TDD	Limited
Output power Restriction	Yes (14dBm = 25mW)	Yes (14dBm = 25mW)	No (23dBm = 200mW)	No (23dBm)	No (23dBm)
Voice	No	No	No	No	Yes
Typical range	15Km LOS	5Km (Urban) 15Km LOS	Deployment-driven 20Km LOS	Deployment-driven ~5Km	Deployment driven 15Km
Transmission Techniques	UNB	FHSS (Aloha)	FDD	FDD/TDD	FDD/TDD

- NB-IoT can be implemented on CRAN to facilitate IoT deployment in centralization and network-virtualization to operate the base band of a base station. Such implementation will improve the performance by deploying a distributed antenna system (DAS) in large buildings or industries. It will also reduce the capital expenditures (CAPEX) by applying network function virtualization (NFV) to the radio-access network.
- The low processing power of the NB-IoT protocol stack and latency requirement enable the implementation of CRAN.
- NB-IoT aids optimization of the access-stratum (AS), also known as RRC, that minimizes the signaling required to discontinue or return the connection of the user plane [38].
- NB-IoT operates in three (3) modes of deployment, namely: in-band, guard and standalone in GSM spectrum. For more information about the mode of operation and frame structure of NB-IoT, readers are referred to [9], [10].

IV. THE OSI LAYER OF NB-IoT FRAMEWORK AND ARCHITECTURE

The NB-IoT OSI reference model, mostly referred to as the protocol stack, does not have a legacy of existence; however, its architectural design is highly rated to provide a connection to over five (5) billion devices through the platform of 5G. The features in the protocol stack that enhance the planning and development of NB-IoT as the most favored energy-efficient version of an IoT warrants studying. According to [44], the layers of the protocol are of the same types as those of the reference model of OSI, developed by the international standard organization (ISO), except for the five (5) upper layers. The layer architecture of NB-IoT is grouped into two planes, namely the data plane and the control plane. The data plane describes the user data flow between two nodes while the control plane describes the protocols that regulate the radio-access bearers and the link connecting the network and the UE. There are six (6) layers of the NB-IoT protocol stack defined by 3GPP as a value-added system for the cellular communication network. The six layers are the physical layer (PHY), media access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP), radio resource control (RRC) and non-access stratum (NAS). The physical layer and the MAC are called the access stratum (AS). The access stratum and the air access methods are the only layers defined by the 3GPP protocol stack which are responsible for handling and processing the physical transmission or reception on the media. The other five upper layers are called the non-access stratum (NAS). The NAS has the same functions and protocols, unique and independent across different physical media. Figure 3 illustrates the difference between the 3GPP protocol stack and the OSI reference model. It is important to note that some of these layers such as the application, session and presentation layers in the OSI reference model might not exist in the control plane.

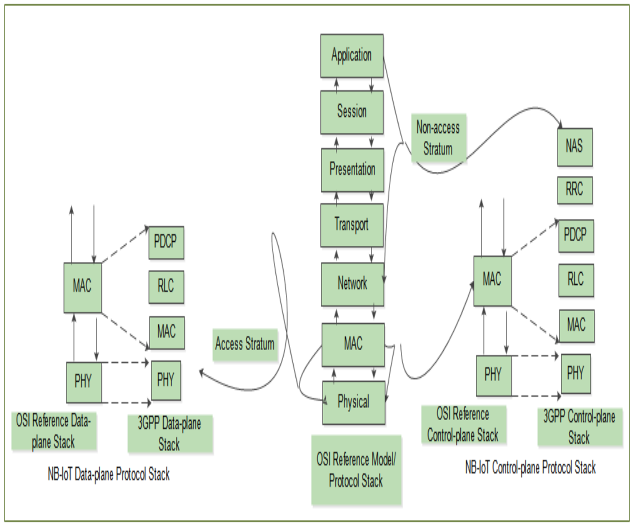


FIGURE 3. The NB-IoT Protocol Stack Architecture vs. OSI Reference Model.

NB-IoT protocol stack uses two movements of exchange of data units, either within or between the protocol stacks. The data units are the service data unit (SDU) and protocol data unit (PDU). The service data unit moves the data unit within the layers. For example, each layer has its SDU appended by the header of each layer when exchanging the SDU to an upper or lower layer (i.e., intra-layer data unit). Also, for the PDU, each layer knows the size of its header. Therefore, when a PDU receives or transmits between the layers of data-plane protocol stacks, the layers either strip off the PDU or add up to the checksum of PDU to extract the SDU from the upper or lower layers respectively.

Understanding the protocol stack of NB-IoT would enhance a systematic architecture required for efficient planning, dimension, cost estimation, design, and network deployment. This will support the international telecommunication union (ITU) for international mobile telecommunication 2020 (IMT-2020). 3GPP has introduced the sublayers of the protocol stack of NB-IoT for 5G NR coexistence.

Figure 4 illustrates the general network architecture of an optimized LTE NB-IoT. The figure simplifies the overall 3GPP LTE NB-IoT network connection to the NB-IoT user equipment (UE), eNodeB, and the core network (evolved packet core (EPC)) to address the IoT traffic model requirements [38], [44]. The LTE core network, known as EPC, has two interfaces with the eNodeB; the S1-MME protocol that conveys all signaling messages and the S1-U that sends all user or data messages. Data plane traffic flows from the UE to eNodeB through the S1-U interface to the serving-gateway (SGW), packet-gateway (PGW) and finally to the internet. Each eNodeB provides geographical coverage of the area. All NB-IoT devices equipped with a universal subscriber identity module (USIM) card are connected to these eNodeB services. Multiple eNodeBs are connected through the X2 interface and protocols. The traffic of the control plane from the UE to the eNodeB is directed through the S1-MME

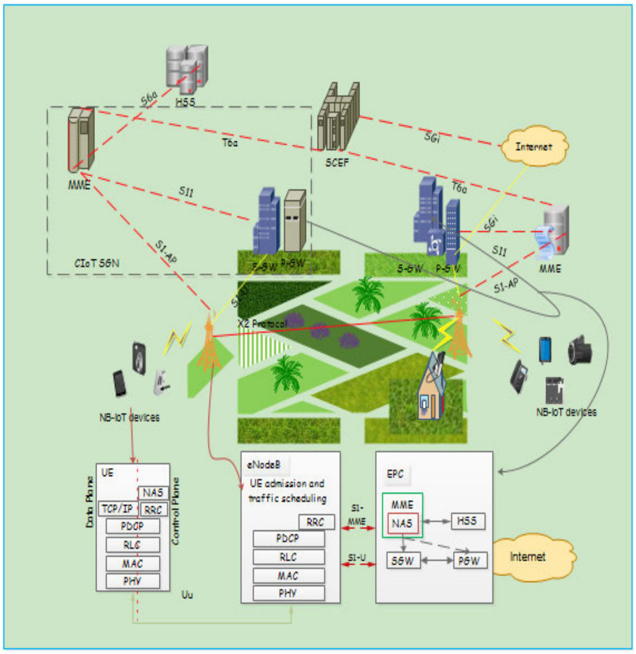


FIGURE 4. The general network architecture of an optimized LTE NB-IoT.

TABLE 2. Functions of LTE NB-IOT Network components

Features	Functions
Physical Layer (PHY)	This is the sublayer at the bottom of the NB-IoT protocol stack responsible for physical channels, transmissions, and receptions of MAC PDUs. It is defined as the air access channel of all NB-IoT devices by the 3GPP, [45]. The configuration parameters of this sublayer are contained in [44].
Media Access Control (MAC)	This is the sublayer interfacing direct with the PHY. It performs multiple functions ranging from multiplexes and demultiplexes of several RLC PDUs, random access and contention resolution procedures, DRX for battery power conservation, hybrid ARQ operation and so on, to mention but few [44], [6]
Radio Link Control (RLC)	In LTE NB-IoT, RLC is an essential sublayer responsible for the guaranteed transfer of control and data plane PDU to the receiver. The design objectives and configuration of this sublayer are presented in [44], [46].
Packet Data convergence Protocol (PDCP) Layer	The sublayer is responsible for providing integrity and security protection to both control plane and data plane PDUs. The architectural design and objectives of this sublayer are contained in [44], [47].
Radio Resource Control (RRC)	This sublayer keeps the UE complexity much lower, suitable for extremely low power consumption, low data speed, and lower cost. The identity of UE components is described in [44].
Non-access Stratum (NAS)	NAS is a signaling layer that establishes communication between UE and the core network. It has evolved and exists with other 3GPP protocol stacks. It manages authentication, mobility management, security control, and bearer management [45], [44].
Serving Gateway (SGW)	SGW receives the packets of the data plane from the UE through the S1-U interface. It is the first component in EPC. If the packets of the data plane from the UE are piggybacked with NAS signaling messages, then the packets are routed through another interface, except for the SGW. The main functions of SGW are contained in [44].
Packet Gateway (PGW)	PGW provides the second gateway to the packet data network (PDN) in EPC. It is an access point that provides connectivity to the UE through the internet, applications, and services [44].
Home Subscriber Server (HSS)	HSS is a component, contained in EPC, responsible for storing and updating UE subscription information, UE information about different security keys for identity and generated tracking encryption [44].

interface to the MME. The role of the MME is to ensure NAS signaling, select the SGW and PGW, provide authentication and authorization, and finally, to lawfully intercept a piggy-backed signaling message or data plane message with the signaling messages. The eNodeBs connects to different MME to avoid overwhelming the MME. Each eNodeB can associate with over hundreds of thousands of NB-IoT devices within the MME region, thereby creating load balancing among the network nodes. Table 2 describes the functions of each feature in Figure 4.

A. THE 3GPP NB-IOT STANDARDIZATION

The NB-IoT standardization in release 13 by 3GPP technical specification group (TSG), for IoT and M2M (MTC) applications, connects many devices in a wide range, on the platform of IoT. The 3GPP is an open-based standard facilitating innovative consensus-based decision-making application of NB-IoT interoperability with cellular networks on the different technology-based systems. The standard creates unlimited technologies crucial for developing IoT applications over cellular technologies. However, much researches on the NB-IoT architecture, emerging technologies, deployment, and standardization are still ongoing. We hope that the collaborative effort to improve the efficiency and connectivity of NB-IoT will promote various enabling global technologies that guarantee security, interoperability, quality of service (QoS), and longevity of IoT applications. Two different data rates have been developed for NB-IoT by 3GPP standard, namely the data rates ranging from 10s of kbps in 180 kHz bandwidth (LTE Cat-NB1) to a few hundreds of kbps (LTE Cat-NB2) [48].

Several other standardization bodies such as IETF, IEEE, ITU, ETSI, etc. (as illustrated in Figure 5) on LPWA technologies projects have also provided a framework for standardized IoT deployment, but despite their efforts, there is still no standard reference for the IoT-platform [49]. The journey of in-depth research into NB-IoT by the 3GPP started in 2015 with release 13 to make MTC services an essential part of 5G networks. Possible problems such as congestion and overload on data and signaling planes, numbering and addressing of resource shortages during synchronous access of many terminals, time-control and so on that hampered its potential were highlighted, and led to the enhancement features implemented in release 14, the three (3) support services introduced such as; eMBB, uRLLC and mMTC in Release 15, and to the focus on full support for the industrial internet of things (IIoT) for industry 4.0, including enhanced uRLLC and TSC, introduction of support for non-terrestrial networks (NPNs), unlicensed spectrum operation, and enhanced deployment by integrated access and back-hauling (IAB) operation, mainly geared towards mmWave networks in Release 16, completed in March 2020. The ongoing work is expected to include enhanced IIoT support

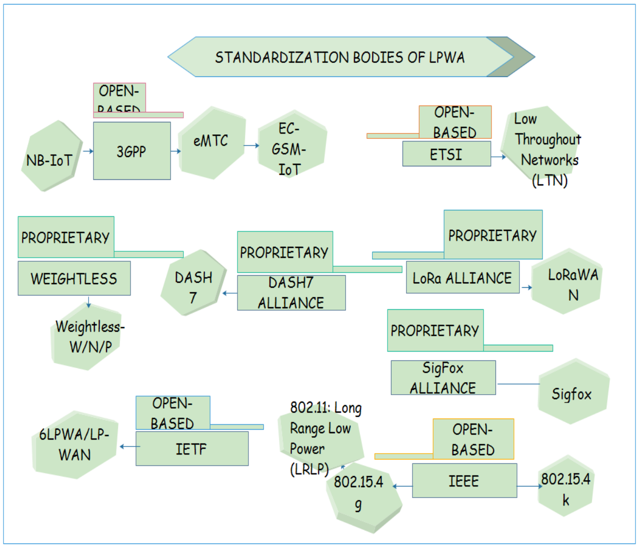


FIGURE 5. LPWA Standardization Bodies.

and enhanced NPN support, enhanced wireless support and wire line convergence, multicast support and enhanced network automation support, including 5G New Radio-light (NR Light) which strives to facilitate light-weight communications for industrial sensors and related applications to be completed in mid-2021. Table 3 lists the features of all the 3GPP releases from Release13 to the current anticipated Release 17. More information about the features described in Table 3 are detailed in [10], [12], [50], [51]. The implementation of 5G NB-IoT will also feature some advanced attributes of massive IoT that include resource spread multiple access (RSMA) for IoT use cases requiring asynchronous and grant-less access, multi-hop mesh, PSM schemes, and eDRX for longer battery life. The benefits of 5G NB-IoT cannot be overemphasized, especially when considering the large-scale deployments and impressive prospects for widespread market success.

V. 5G ARCHITECTURAL DESIGN FOR NB-IoT INTEGRATION

NB-IoT incorporated into the ongoing 3GPP 5G architectural design was possible by using wireless software-defined networking and the network function virtualization (NFV) paradigm [57], [58] through the relationship between the 5G radio access network (RAN) and the 5G architectural infrastructure. The introduced WSDN and NFV created cost-efficient service support for the NB-IoT model to facilitate communication between NB-IoT devices and applications. To buttress this point, we examined the limitations in EPC developed by 3GPP for LTE cellular network as illustrated in Figure 4. The limitation in EPC influences the latency of the overall system. One primary concern is inseparability of the control and data planes in the EPC. This has led to the coupling level between SGW and PGW that reduces the quality of service (QoS) of the network. Decoupling of the control plane and the data-plane becomes essential, since

TABLE 3. Features of 3GPP standard release

Freezing time	Version	`Technologic fields of concern
2016	R13	Newly developed 180kHz physical-layer channels and signal, RF-bandwidth, half-duplex, 3 operational mode (Standalone, inband and guard band), multitone and single tone on the uplink, RRC connected/suspended, transmitted data through control plane, eDRX, mobility only idle mode. [51].
2018	R14	Newly improved UE power class of the mission-critical (MC) aspects, such as the video and data MC-services. Introduction of vehicle-to-everything (V2X) communications, such as vehicle-to-vehicle (V2V), improved cellular internet of things (CIoT) by 2G, 3G, and 4G MTC support, improved radio interface for enhanced coordinated WLAN and unlicensed spectrum [52].
2019	R15	Power consumption reduction, reduced latency, improved accuracy, reliability of random access and enhanced range, small cell support, TDD support, enhanced access barring, enhanced eDRX, additional enhancement of critical communications for both uRLLC and high-reliable low-latency communication, MTC and IoT, vehicle-related communications (V2X), MC and WLAN-related features and unlicensed spectrum [53].
2020	R16	5G phase 2, due for June 2020 completion with a focus on multimedia priority service, application of vehicle-to-everything (V2X) services, 5G satellite-access, 5G local area network support, 5G wireline convergence, and wireless, terminal location and positioning, vertical-domain communications and network-automation, and novel radio technique. Additional items comprise security, codecs and streaming services, interworking of local area networks, network slicing and IoT, Inter RAT cell-selection, co-existence with NR, UE-group wake-up signal [54], [55].
2021	R17	The work addresses RAN 1, RAN 2, and RAN 3: physical layer, radio protocol, and enhanced radio architecture. Various characteristics of RAN 1, necessary for overall efficiency and 5G NR performance; MIMO, improved spectrum sharing, UE power saving and enhancement in coverage will be implemented. RAN 1 overview and specifications for improvement in the physical layer in support of frequency-bands beyond 52.6GHz up till 71GHz. [56].

both control plane and data plane have different network QoS criteria to be met. The control plane requires low latency to process signaling messages, and the data plane needs a high throughput to process the data. Therefore, for efficient design of a plane, it is desirable to decouple the planes completely.

Another limitation is the centralized implementation of the data plane of the LTE EPC. This limitation creates in-efficiency in system performance and a high latency that do not satisfy the 5G NB-IoT criteria [59]. The result of this limitation is witnessed when a user transmits traffic meant for local communication through a hierarchy system ending with a few numbers of centralized PGW. This effort increases the end-to-end (E2E) latency as illustrated in (1) [60].

$$T = \sum (T_{\text{Radio}} + T_{\text{Backhaul}} + T_{\text{Core}} + T_{\text{Transport}}) \quad (1)$$

where T is the total one-way transmission time contributed by the RAN, Backhaul, Core network, and the data center (Internet). The T_{Radio} is the packet transmission time between the eNB and UE, which is due to the physical layer communication. T_{Backhaul} is the time it takes to establish interaction (connections) between eNB and the Core network (i.e. EPC).

T_{Core} is the time taken by the Core network to process the signal and finally, the $T_{Transport}$ is the communication delay between the core network and the cloud (internet).

Note that the centralized implementation of the network enhances the ease of managing and monitoring the system, but hindered the network QoS. The WSDN is an important pillar that separates the control plane and the data plane. Hence, support load balancing, reshapes enterprise network design, tackles the classes of complexity in the 3GPP 5G networks, and the IoT, and creates an excellent QoS for the network. The NFV, on the other hand, coordinates dynamic network resource sharing to promote the high-flexibility network.

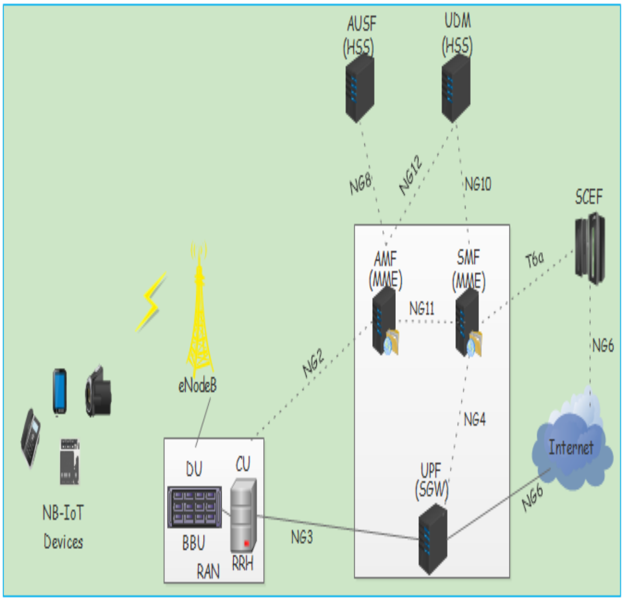


FIGURE 6. The proposed NB-IoT functional architecture for the on-going 3GPP 5G networks (adapted [38], [57]).

The decoupling of the RAN promotes serviceable segregation of the broadband unit (BBU) from the remote radio head (RRH) that meets the condition of the interface of the 5G NB-IoT specifications [61]. Figure 6 describes the proposed NB-IoT functional architecture for the ongoing 3GPP 5G networks. The proposed NB-IoT architecture consists of network functions (NFs) and reference points (NG) connecting the NFs. Figure 6 comprises seven (7) NFs, namely the distribution unit (DU) and centralized unit (CU), and the access and mobility function (AMF), the session management function (SMF), the authentication sever function (AUSF), user data management (UDM), user plane forwarding (UPF) and service capability exposure function (SCEF). The RAN connects the UE as well as the AMF. The RAN comprises two logical architectural components, namely the DU and CU. The DU and CU have the same functions as the existing LTE BBU and the RRH respectively. Both components support signaling exchange and data transmission between radio access interfaces (endpoints) of the NB-IoT specifications [62]. The remaining NFs are explained as follows [38], [57];

1. The primary task of AMF is to allow UE-based authentication, authorization, mobility management, connection management, and so on, including various functions related to security management. AMF performs the same features as the MME in the LTE network. It is independent of the access technologies. This can be seen when a UE with multiple access still upholds the connection to a single AMF.
2. The SMF is accountable for the session management context with the UPF just as in the LTE MME, SGW-C, and PGW-C. Amongst the functions performed by the SMF are allocating IP addresses to UEs, NAS signaling for session management, sending QoS and information policy to RAN through the AMF, DL data notification, controlling, and selecting UPF for traffic routing. The UPF function selection facilitates the mobile edge computing (MEC) by selecting a UPF close to the edge of the network and so on, to mention but few.
3. UDM stores UE subscription data.
4. AUSF stores UE authentication data.
5. UPF is the UE mobility anchor that promotes the UE traffic backwards and forwards into the internet.
6. SCEF ensures the delivery of non-ip data over the control plane and provides an abstract interface for network services such as authentication, access control, or discovery.

The UPF is in the user plane and carries user traffic while the remaining NFs (AMF, SMF, AUSF, and UDM) are in the control plane. The user and control plane separation ensure that the resources in each plane scaled, will be independent. Also, the UPFs deployed will be distributed differently from the control plane functions. For example, UPF deployed, connect to the UEs to reduce the round trip time (RTT) connecting UEs and data network for promoting applications with low latency [57].

The global acceleration of NB-IoT design in the 5G NR air interface standard was aimed at providing smooth transition and continuity of large-scale mMTC to 5G networks. More importantly, for ensuring technical guarantee for the operators, equipment vendors, chip manufacturers, and vertical industries in creating R&D and business model exploration [55]. The human user experience is expected to be enhanced by various 5G-enabled machine-related use cases through the 5G NB-IoT transformation. According to GSMA, altogether 129 NB-IoT and LTE-M commercial mobile-IoT networks have already been launched from January 2020 [63] with coverage of approximately 93% of the world's largest IoT market in Q2 2019 [42]. The total number of NB-IoT (and IoT in general) connections expected is to rise to 25 billion by 2025 with a growth in application platforms and services to the tune of 68% of IoT-revenue of \$1.1 trillion [63]. The transformation will provide a matured industrial-chain from a developed policy-driven to service-driven NB-IoT growth in the future when fully commercialized. The service-driven will, in turn, drive unquantified satisfaction and pleasant experience in human activities and industries through its deployment to various aspects of life activities. However, the challenges and related issues of NB-IoT implementation need to be considered from multiple perspectives such as enabling technologies, service and applications, business models, environmental and social impacts [64]. The enabling technologies necessary to address the required 5G NB-IoT can be grouped into the spectrum and network-enabling technologies [4], [65].

A. THE ENABLING TECHNOLOGIES REQUIRED FOR 5G NB-IoT

The network-enabling technologies are:

- Network densification through small cells
- Cognitive radio (CR)
- Massive multiple-input multiple-output (MIMO) antennas (beam forming)
- Distributed network
- Cloud-based radius access network (CRAN)
- Wireless network function virtualization (WNFV)
- Wireless software-defined networking (WSDN)
- Edge computing to support low-latency application
- Control and user plane separation
- Network slicing (network as a service) to support application specific QoS
- Real-time machine learning/artificial intelligence
- New fronthaul, mid-haul, backhaul solutions and the spectrum-enabling technologies which are:
- New band (3.5GHz mm wave)
- Efficient use of spectrum through spectrum-sharing techniques such as licensed shared access (LSA)
- Large bandwidth to support the required data flow
- Using unlicensed band to offload the traffic

The key technology enablers for realizing 5G NB-IoT networks are the two wireless SDN and NFV, as stated earlier. Both software technologies define the methods of the deployed and operated network services. The two technologies enable network slicing to provide customized QoS and specific functions required for different vertical markets. The CRAN cut down the total cost of operational expenditure (OpEx) to facilitate efficient resource allocation. The improvement in spectrum reuse and network capacity was achieved through the deployment of small cells. The new backhaul solutions assist both the traditional and distributed RAN networks to ensure user connectivity. The edge computing employed for local analysis and data processing enhances the users' quality of experience (QoE) with improved visual, audio and haptic interfaces. The implemented MIMO increases the user data speed and system capacity for 5G NB-IoT requirements. Data transmission and reception over the same radio channel are enhanced through highly focused beams by exploring multipath propagation and spatial multiplexing. The CR techniques employed can identify available free spectrum (spectrum sensing), detect licensed users, select (spectrum management) and vacate the best possible spectrum on the arrival of the primary user (spectrum mobility) [66].

Since 5G NB-IoT-operated systems will be in NR of a higher frequency band than LTE, the bandwidth offers a high-frequency band of much wider channels and high speeds beyond 1GHz. The use of technologies such as MIMO, macro-assisted small-cells, and super-dense meshed cells supports the varying requirements of all use cases. Spectrum-sharing techniques, such as licensed shared access (LSA), enhance spectrum utilization, while unlicensed spectrum, coupled with licensed spectrum, increases the access to network capacity and improves users' wireless experience.

VI. THE CLOUD-ASSISTED RELAY WITH AMBIENT BACKSCATTER COMMUNICATION FOR 5G NB-IoT NETWORKS

Before the implementation of CRAN, the interaction among base stations (BSs), radio access network (RAN) and a core network, as well as the direct X2 interface between RANs operating in separate cells, was based on Internet protocol (IP) (as in the case of flat architecture of core network in LTE) [67]. This, however, restrained handing-over procedures for mobility management, increased inter-cell coordination for interference management, and joint transmission of baseband signals through coordinated multipoint (CoMP) [61]. With the multitude of RATs and HeterNet configurations to be deployed in 5G NB-IoT, managing and deploying large networks can be challenging and expensive without the implementation of CRAN.

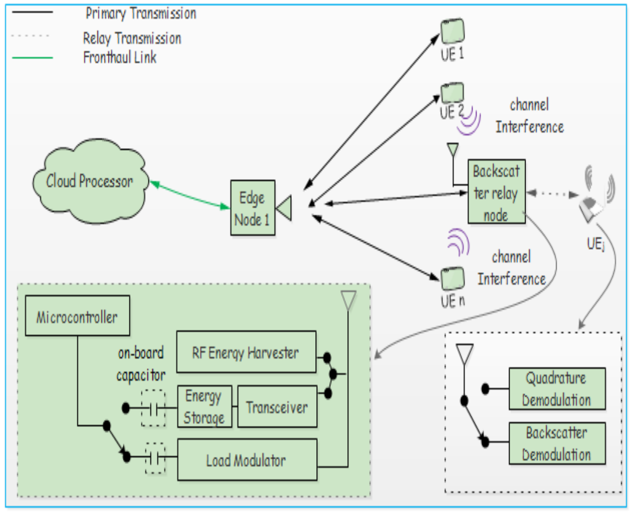
The adoption of CRAN provides a solution to the above challenges and also allows tremendous connectivity, resource pooling, spectral, and energy efficiency for supporting the practical roll-out of NB-IoT, as well as the centralization of baseband (BB) processing functions of BS demanding architectural changes to RAN components. The RAN protocol stack of NB-IoT has to be flexible to adapt complex signal-processing and radio resource management (RRM) functions [68]. Though NB-IoT deployment can be a software upgrade to an existing LTE network, it can also be accomplished in a 5G-enabled cloud-RAN due to its simplified baseband processing and signaling protocol. The simplified baseband processing and signaling protocol provide cost-effectiveness in deploying and executing NB-IoT on a general cloud computing infrastructure or virtual machine (VM) using software-defined radio (SDR) [17]. The virtualization of RAN has been possible in NB-IoT due to the narrow bandwidth that requires an off-the-shelf network router for its modest fronthaul link capacity. Another feature of NB-IoT suitability for CRAN was the relaxed-latency requirement. The relax latency permits the BS to operate in very restricted computational power conditions due to the asynchronous HARQ design when compared to the legacy LTE. In such a situation, NB-IoT can profit from the deployed processing delay flexibility caused by multiple hops in cloud infrastructure. This implies that the remote radio units (RRUs) can be located further away. Therefore, the baseband unit (BBU) server can traverse a larger area [61].

The enhanced coverage area of cloud NB-IoT BS also creates the possibility of NB-IoT femtocell deployments for large buildings and industrial sites due to the signal repetitions and increased power performance gain. However, the repetition is constrained by channel estimation accuracy that depends on the received signal-to-noise ratio (SNR) and the channel coherence time [17]. Also, the efficient realization of CRAN is challenged by factors such as the scalability, latency requirement, and fronthaul capacity constraints as well as the network resource slicing between IoT applications and other broadband services [17]. The fronthaul link between the BBU and remote radio head (RRH) reduces the amount of processing time available for the BBU before the HARQ feedback time expires. Further information about CRAN implementation can be found in [61]. The reports on ambient backscatter [69], data compression [70], and power-saving [71] mechanisms have been highlighted to meet the challenges of fronthaul capacity, latency problems, and co-channel direct-link interference (DLI).

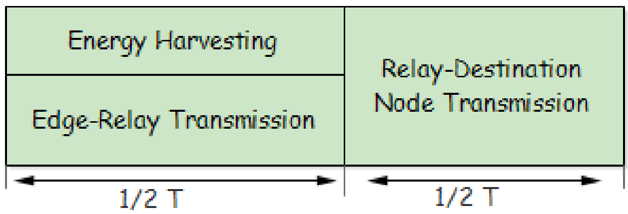
Ambient backscatter paradigm is an emerging technology that can harvest energy from external sources to extend the lifetime of wireless NB-IoT devices with the exclusion of strict battery constraints involving any type of power-consuming active components or other signal-conditioning units. Ambient backscatter can be designed to use wireless information and power transfer (SWIPT) mechanism [72], [73] through the exploitation of existing or legacy RF signals (such as cellular, TV, WiFi, or radio systems) [74] for effective deployment of cloud NB-IoT network. The incorporation of ambient backscatter relay technology into the cloud NB-IoT network will increase communication distance, channel capacity, and diversity, as well as link reliability [69], [75], [76]. The research work from [69], [72] provides a guide to effective implementation of a cloud-assisted relay with ambient backscatter communication for 5G NB-IoT networks. Figure 7 illustrates the conceived architectural design of the cloud-assisted relay for 5G NB-IoT networks. In Figure 7a, the edge node provides bi-directional radio functionalities for transmitted/received signals to/from the UEs within and outside the coverage area of the network. Each UE is provided with a dedicated channel (i.e. UL/DL channel) to interact with the edge node, including the relay node E placed on the same channel. It can be assumed that OFDMA has been employed by the edge node to allocate resources to the UEs and the relay node E respectively. Also, the following assumptions can be made to achieve an effective system [76]:

1. All UEs should be equipped and powered by a battery, single antenna, and operated in half-duplex mode.
2. The relay node E should be equipped with energy-harvesting capacity for its operation. Moreover, E should be allowed to relay information through either active radio or passive ambient backscatter, termed Active-relaying and Passive-relaying.
3. The node UE_j is located far apart from the edge node coverage and transmit power budget. Hence the information from the edge node passes through the relay node E to reach the node UE_j.
4. The relay node E has a power-splitting (PS) based receiver architectural design [77] for conducting simultaneous information decoding and energy harvesting. The relay node E should function as energy harvester to charge the on-board capacitor of the adopted circuit components.

Once the circuit is fully charged and powered-on successfully, the excess harvested energy is reserved in energy storage for intended active communication. The relay node E adopts decoding and forward protocol procedure by using the time slot model to perform mode selection as depicted in Figure 7b. During the edge-to-relay transmission, a portion of the aggregated RF signal collected from both the energy sources and interferers (i.e. co-channel interference)



(a)



(b)

FIGURE 7. a. The conceived architectural design of the cloud-assisted relay for 5G NB-IoT networks (adapted [72], [76])[1,2]. *Copyright©2018 & 2019, IEEE.*
[1] Republished with IEEE permission from "Cloud-Aided Cognitive Ambient Backscatter Wireless Sensor Networks", D. Darsena, G. Gelli, and F. Verde, vol. 7, pp. 57399–57414, 2019. Copyright.
[2] Republished with IEEE permission from" Performance Analysis of Wireless-Powered Relaying with Ambient Backscattering, X. Lu, G. Li, H. Jiang, D. Niyato, and P. Wang, pp. 1-6, 2018.
b. Time Slots Model of Power Splitting based relaying protocol for performing mode selection (adapted [76])[2]. *Copyright©2018.*

is utilized for harvesting and the overflow is used for information decoding to transmit preamble signals from the E to the node UE_j in the first half of the time slot. The process is termed active relaying mode (i.e. the energy harvesting rate of E ≥ twice the circuit power dissipation in the active state). Otherwise, E chooses a passive relaying mode. At the node UE_j, a feedback of the received signal-to-interference plus noise ratio (SINR) through the signaling is granted depending on the relay transmission ratio of the active and passive relay modes. If the received SINR at the node is greater than the active time slot, E chooses active relaying mode and the nodes work with the quadrature demodulation. Otherwise, E chooses the passive relay mode and the nodes work with the backscatter demodulation. This proposed process can estimate channel parameters by using a standard technique for all the UEs associated with the cloud. Also, the interference contribution can be subtracted from the received BB signal, thereby solving the challenge of interference instead of applying complex multiple antenna techniques as discussed in [77]. It is worthwhile to mention that the performance of the backscatter relay node E neither suffer the latency from the edge node nor be affected by the performance of the UEs appreciably [78].

VII. 5G NR AND NB-IoT COEXISTENCE

NR specifications were approved in March 2017 by 3GPP as part of release 15 [79] and release 16. Since then, many operators (both existing and new) have commenced migration from LTE to NR, with the United States leading in 2019, due to the flexible deployment of NR. NR key features are contained in [79], [80]. The NR coexistence with NB-IoT can enhance resource efficiency and avoid mutual interference between the two networks, though, NR channel bandwidth flexibility has some numerology similar to that of LTE and NB-IoT as tabulated in Table 4. The subcarrier orthogonality between NR and NB-IoT can be obtained by examining specific design limitations that need to be overcome, for example interference, scheduling, and resource utilization. The resource utilization through the aligned resource blocks (RBs) between the NR and NB-IoT can be improved.

The feature of FDD bands as listed in Table 4 enables NR tractability to examine effectively deployed NB-IoT within the NR carrier. For instance, the deployed in-band NB-IoT within the NR carrier requires the guard band reserved to forestall interference between the NR and NB-IoT. The listed parameters to be exploited [81] are:

1. NR resource reservation in the time domain (symbol level) and frequency domain (RB-level) configuration using a flexible method.
2. System bandwidth choices, as well as raster steps requirements.
3. Placement of synchronization signal block (SSB) in an NR carrier.

Generally, the air interface of NR is flexible and can meet the general requirements of several NB-IoT use cases and deployments by adapting the scalable cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) waveform of NR. The scaling factor 2^{μ} helps to align the slots and symbols of different numerologies in the time domain to secure TDD networks. However, for NB-IoT to sustain use cases with diverse requirements simultaneously on the same NR carrier, two options have been suggested [82];

1. The use of minislots between regular slots, to enhance low latency and avoid extended CP overhead. The use of minislots can also expeditiously enable transmissions in an unlicensed spectrum, as well as schedule users on a short time scale.
2. Frequency domain multiplexing (FDM) of numerologies is another option. The use of FDM results in internumerology interference. Therefore, spectral confinement of waveform becomes essential. The low-complexity windowing/filtering and slight guard band overhead can be adopted to reduce internumerology interference. The windowing method can also be adapted to enhance asynchronous access to mMTC applications.

For instance, the author in [84], employs 700MHz wireless band standards of which 10MHz bandwidth was shared between 5G NR, LTE-A and three (3) NB-IoT DL carriers. The three (3) NB-IoT carriers have different operational

TABLE 4. The similarities between the numerologies of NR and NB-IoT [79], [81], [83]

Features	New Radio (NR)	NB-IoT
Frame structure	Consists of 10 subframes, each of 1ms duration. The sub-frame consists of 2^{μ} slots of 14 OFDMA symbols each	Consists of 10 subframes, each of 1ms duration. Each subframe has 2 slots of 14 OFDMA symbols each
Subcarrier spacing	Has adjustable sub-carrier spacing of 2^{μ} *15kHz, where μ =0, 1….,4. This identical property (when μ=0) facilitates coexistence between NR and NB-IoT.	Has subcarrier spacing of 15kHz in DL and 3.75kHz in UL
Resource block (RB)	RB contains 12 subcarriers in the frequency domain and has one dimension. The bandwidth of RB relies on the subcarrier spacing. For example, with 30kHz subcarrier spacing, each NR RB has 360kHz and 180kHz for 15kHz subcarrier spacing.	RB is two-dimensional in the time and frequency-domain. It also has 12 subcarriers. The bandwidth of the 15kHz subcarrier spacing is 180kHz.
Raster grid	Describes a subset of RF reference frequency employed to distinguish the RF channel region in DL & UL. The raster step relies on the carrier frequency. The reference frequency of the RF channel is related to the resource element on the carrier. Therefore, for initial access, the UE explores its carrier across the raster grid.	Raster designates the center of the carriers. Hence, the NB-IoT raster is midway between two subcarriers in the NB-IoT RB.
FDD Frequency bands for NR and NB-IoT deployment	Bands (1,2,5,8,20.25.28.66) have NR channel bandwidth for 15kHz subcarrier spacing (MHz) of 5,10,15, & 20. Band (3) has (5,10,15,20,25, & 30), Band (12) has 5,10 & 15 and Band (77) has 5,10,15,20, and 25, respectively. The channel raster of 100kHz is used for them all.	This is the possible NB-IoT carrier's center locations relative to NR

mode of two (2) guard band mode and one autonomous mode located at the center of the spectrum. This scenario is termed as dynamic Spectrum sharing (DSS) as specified in 3GPP rel. 15. To achieve an effective coexistence and avoid collisions, 5G NR must be configured with 15kHz subcarrier spacing to ensure the synchronism signals out of band of LTE signals. Again, since the maximum delay spread of NB-IoT guard band is the LTE-A cyclic prefix (CP) length (i.e. 4.7 μs), precaution is critical in the planning of the network to avoid interference for the first OFDM subcarrier of LTE-A.

The fundamental abstract above about coexistence of NR and NB-IoT will form the foundation of prospective NB-IoT design supports for diverse use cases and applications on NR carrier, based on the choice of the parameter μ (μ depends on several factors, including deployment types, service requirements, hardware impairments, mobility, performance, and implementation complexity) [82].

A. POTENTIAL ARCHITECTURAL DEPLOYMENT SCHEME OF NB-IoT WITH CELLULAR NETWORKS

5G networks and the currently deployed LTE networks consist of macro-cell and small-cell infrastructures of heterogeneous networks. The overlaying of small cells on macro-cells results in interference, which affects small-cell edge users and NB-IoT UEs towards obtaining adequate QoS in the NB-IoT network. In order to enhance the NB-IoT performance in a small-cell network, based on spectral efficiency, coverage and capacity over the heterogeneous infrastructures (macro-cell and small cells), four categories of possible support for NB-IoT coexistence with the legacy LTE and the ongoing 5G networks listed in [10], [85] are:

- Synchronous distribution of NB-IoT in all small cells
- Asynchronous distribution of NB-IoT in all small cells
- Synchronous distribution of NB-IoT in small cells and macro-cells
- Asynchronous distribution of NB-IoT in small cells and macro-cells.

a) Synchronous Distribution of NB-IoT in all small cells

In this scenario, all synchronized small cells appear in a mode to make use of the same PRB. All NB-IoT UEs configured should apply an identical transmit power despite the highest transmitted power capacity, to limit the creation of co-channel interference to many UEs on similar radio resources. The power restriction requires a practicable innovation that ensures satisfactory performance. Despite this, cell edge UEs may still experience interference difficulty due to the associated low quality of channel estimation of NB-IoT UEs to reduce computational complexity.

b) Asynchronous Distribution of NB-IoT in all Small-cells

This scenario involves a precise frequency plan, as well as a specific-power configuration for NB-IoT UEs. NB-IoT enabled is devised in all the small-cells utilizing unique PRBs. This strategy prevents interference among NB-IoT UEs of diverse small cells but may cause co-channel interference within the NB-IoT and 5G NR/LTE UEs employing similar radio resources. Several techniques proffered to mitigate this co-channel interference need further enhancement. Conventional methods are blanking and frequency hopping. The blanking technique referred to as a wasteful technique will be avoided.

c) Synchronous Distribution of NB-IoT in Small Cells and Macrocells

The approach facilitates NB-IoT in both the small cells and macro-cells with different transmit powers on a similar PRBs. The macro-cell UEs configured should use higher transmitted power than the small-cell UEs. The remaining PRBs configured are used for 5G NR/LTE. Co-channel interference may arise on small-cell edge UEs if the UEs scheduled are on identical resource units. The effect of the interference may increase on UEs requiring handing-over from one serving cell to another. Frequency reuse, power control, frequency hopping, and geographical planning may be needed urgently for low-complexity NB-IoT to improve the coverage range of NB-IoT.

d) Asynchronous Distribution of NB-IoT in Small-cells and NR/LTE in Macro-cells

The approach estimates various variables such as the use case specifications, environmental limitations, equipment status, and so on to guarantee improved spectral efficiency, performance, and extensive NB-IoT distribution with other technologies. The approach employs separate PRBs for NB-IoT among small cells and macro-cells intending different PRBs for small cells and macro-cells. The strategy requires effective PRBs planning to avoid interference from an adjacent cell of NB-IoT users with identical resource units. It is also likely that NR/LTE users with similar resource elements might conflict with the small cell or macro-cell UEs. Different transmitting power control configurations are applied to prevent interference.

VIII. TECHNICAL PERFORMANCE PROPERTIES OF NB-IoT

The technical properties of NB-IoT can be grouped under two layers i.e. the PHY and the MAC layers. Features such as coverage area, scalability, transmission data rate, physical channel estimations, and MAC PDU reception applicability are referred to as PHY properties while the design and enhancement of protocols that support energy management, link adaptations, resource allocation, security, and coverage enhancement are referred to as the MAC properties. The PHY layer has been called a layer that accommodates most of the innovation and novel inventions of the NB-IoT features. The study of both layers (PHY and MAC) was necessary to discover the plethora of research gaps and proposals for future research into NB-IoT stack optimization towards 5G mMTC requirements. However, NB-IoT employs a similar protocol stack as the legacy LTE, with design modifications in PHY/MAC layers, which has introduced an added +20dB MCL support.

At the MAC/PHY interface, the transport channels are mapped to physical channels and vice-versa at the transmission and reception [44], which allows multiple interactions within one LTE PRB of NB-IoT. The data channels, control, broadcast, and random access are all multiplexed on the same radio resource. This relates to when and how the radio resources shared among the NP-RACH, NP-USCH, NP-DCCH, and NP-DSCH can significantly affect the services rendered and the device performance. The effect of these parameters has prompted researches on downlink control information (DCI) search space under a different set of coverage classes as they relate to control channel allocation and data scheduling. The scheduling process allocates radio resources to UEs in every transmission time interval (TTI) through the DCI in NP-DCCH. The NB-IoT scheduling process is located in the lower MAC and upper PHY layers [9], [86]. The DCI specifies the scheduling information for uplink and downlink transmission in every base station of NB-IoT. The UE specific DCI for procedures such as paging, random access, and data transmission carried by the NP-DCCH are to deliver scheduling command. The DCI defined occurs in three (3) formats, namely the DCI format N0 has a payload of 23 bits and is responsible for carrying NP-USCH scheduling grants. The NP-USCH scheduling grants comprises the repetition number, modulation and coding scheme (MCS), resource assignment, scheduling delay and subcarrier sign. The DCI format N1 has a payload of 23 bits and carries NP-DSCH scheduling control and the NPRACH contention-free procedure preamble which consists of DCI format N0, including ACK resource index of the HARQ process. The last DCI format N2 has a payload of 15 bits and carries both paging and direct sign messages for NPDSCH.

For the UE to discover the DCI messages, the UE tracks the search spaces of the predefined NP-DCCH within the boundary of the subframes allowed for NP-DCCH. The distance between two successive NP-DCCH (NP-DCCH period) is referred to as the $R_{max} \times G$ subframes long, where R_{max} is the maximum repetition number of DCI and G is a system parameter. Since the NPDCCH allocation determines the scheduling opportunities, the combination (R_{max}, G) is also critical for resource scheduling [86].

The resource scheduling issue has prompted state-of-the-art research into data transmission towards scheduling parameter selection and DCI search space allocation. To study the effect of extensive resource consumption per data transmission, a large amount of energy is consumed during the implemented coverage enhancement (CE) features, latency, co-channel interference, design optimization, channel estimation and error correction, among others, on NB-IoT channel communication and resource management. Therefore, we present a brief reviewed works of the literature on the above-listed topics listed to identify the research gaps with a view to enhance the 5G NB-IoT system's performance.

A. NB-IoT CHANNEL COMMUNICATION

This section explains the connectivity procedure of a UE in an NB-IoT network and goes further to review the research gaps in every step of the established connectivity between the UE and the eNBs. The first operation executed by the UE in DL is the acquisition and synchronization of system information. The UE retrieves the cell and access configurations. The synchronized time required ranges from 24ms to 2604ms for high-grade and poor propagation conditions. To communicate with the UE in idle state, the network transmits paging information to the UE through the NP-DSCH by using Format N2. The paging information can be either a request to set up a remote radio-control (RRC) link or it may be due to a variation in the system parameters. After the process of paging (i.e., UE connection status), data acquisition can commence. The DCI Format N1 shows the resources allocated, the DL transmission span, the subframe number, and the ACK/NACK resources applied. The conferred repetition number allows the eNB to transmit identical copies of the data in continuous DL sub-frames without the adopted S1 message subframe through one interleaving subframe. If no repetitions apply, the transmission is outlined in a consecutive DL subframe [87]. The designated repetition number depends on the strength of the signal transmitted from the eNB to the UE [86].

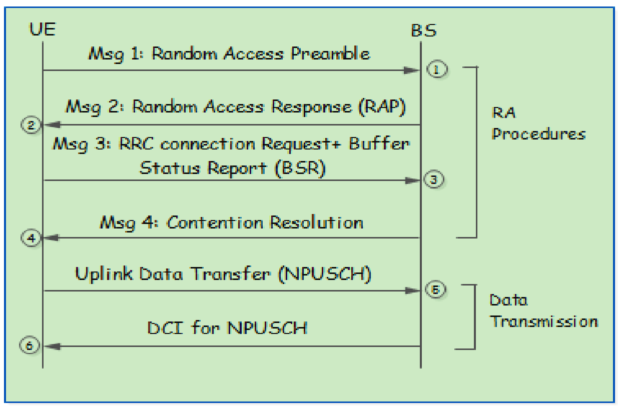


FIGURE 8. RA procedures and data transmission for UL transmission in NB-IoT [88].[3]
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For the UL procedure, access is usually random (RA). There are two methods of initiating the RA. The first method is by a response to a paging message while the second method is by a UE-initiated operation during data transmission. In triggering the RA, the UE demands the system configurations. In the idle state, the UE already has the system information, but for the PSM mode, the UE reacquires the master information block (MIB), system information (SIB1 and SIB2). The RA procedure is always contention-based, and there are four procedures as demonstrated in Figure 8. The first step begins with the preamble signal transmission

(Msg1) to the eNB to initiate the RA [88]. If there are multiple UEs with the same subscriber sending preamble signals, the preamble sequences will collide, and the eNB is yet to be aware of the situation. After the transmitted Msg1, the eNB schedules a DL transmission for the random-access response (RAR, Msg2) through the NP-DCCH and NP-DSCH.

This lasts for about 2-10 times the NP-DCCH period. At this time, the RAR responds to the preamble and grants the next message. The maximum amount of preamble considered per RAR is network-specific and frequently utilized to regulate the load. The UEs without Msg2 in the RAR window, set up a different RA requests. At this stage, the colluded UEs experience an identical RAR without being aware that a conflict has occurred. After Msg2, the UE forwards a link request via the UL by utilizing resources pre-allocated in RAR (Msg3). Msg3 conveys a message such as the UE-identity and the buffer size report (BSR). The UE also commences a contention resolution timer (1-64 times of NP-DCCH period) to wait for the Msg4 on the NP-DSCH. After reception of the link request (Msg4), the eNB schedules the set-up information in the DL to end the RA processes. The UL message (Msg5) from the UE sets the RRC link known as the NAS service request. If any of the procedures of RA fails in the listed steps, the UE will set up a new request after a back-off time of up to $\sim$ 9 minutes. If the UE has exhausted all the trials as configured by the network and up to 10, the UE will have to try in a different coverage class. The UE can attempt for the relatively configured number of 200 before declaring the RA failure. After the RRC link has been secured, the core network commences the transmission of DL information, also known as NAS service data for mobile terminated (MT) DL data-packet communication [87], [88].

B. CELL SYNCHRONIZATION AND ACQUISITION

NB-IoT UE performs cell synchronization and acquisition by using PSS/SSS to obtain the system configurations as mentioned earlier. This information consists of cell ID, scheduling information, number of a subframe, and allocated system bandwidth. Poor cell synchronization and acquisition performance occur when there is a low complexity of devices caused by poor channel estimation capacity and carrier frequency offsets. Usually, the PSS/SSS is located at the center of the carrier in NB-IoT, and all UEs must search all possible carrier positions. This retards the acquisition of system information for any UE without prior knowledge of the position of the carrier frequency. Therefore, for an effective 5G NB-IoT system, there is a need for a fast cell search to be adopted. Many types of research have tried to proffer solutions to optimize the initial cell synchronization and acquisition procedure. The research work in [89] proposes a comprehensive synchronization signal structure design for low-cost NB-IoT in a broad frequency offset scenario for DL synchronization signal design. The synchronization signal with a conjugated Zadoff-Chu (ZC) couple of sequences has been used to eliminate timing issues caused by the large frequency offset. The ZC sequence witnesses a small loss of energy detection due to the insensitivity to the frequency offset. The result of the simulation illustrates a timing detection performance loss of approximately 2dB under large frequency offset in the range of −40kHz to 40kHz when compared with NPSS. The limitation of this model is the fact that there are no records of the number of samples per symbol employed to obtain the simulated results. The research of [90], proposes frequency diversity (FD) reception for narrowband NPSS and NSSS at a UE to enhance the PHY cell identity (PCID) detection probability for NB-IoT deployed in multiple resources blocks (RBs). The reception of NPSS and NSSS by the UE in the time domain transmitted from different RBs within the same frequency band demonstrates link-level simulation results of approximately 16% improvement for PCID detection probability using FD reception, compared to without FD reception of the four RBs with single antenna transmission. Besides, the simulation results of 90% and 97% of PCID detection, probabilities using FD reception are achieved with precoding vector switching (PVS) diversity transmission at an average received SNR power of 0dB for both maximum frequency offset of 70kHz, and without frequency offset respectively. The results of the simulation prove the efficiency of the proposed FD reception towards improving the NPSS detection probability without changing the NB-IoT radio interface.

C. RANDOM ACCESS PROCEDURE (RAP)

For the 5G NB-IoT system, RAP is employed for uplink transmissions between UEs and eNB to achieve system configurations. However, during the multiple UEs transmission of preamble signals with the same subscriber, there is performance degradation resulting from a collision in the network. This is due to the fact that RA is a contention-based mechanism that is not synchronous with the LTE nature at every cell change. Therefore, several investigations and solutions have been proposed in the literature. The author in [91] has emphasized the power consumption challenge faced when the eNB received superimposes NPRACH preambles from massive connectivity of multiple users [92] and the different repetitions of preambles for different coverage areas [93] per transmission over channel probabilities due to collision. The authors have analyzed the increment in the average energy consumed, compared to the increase in the number of repetitions, and they propose a novel power-efficient RAP (PE-RAP) to reduce the power consumed by NB-IoT devices in a highly congested environment. The research of [94] has presented two solutions for RA. The first solution is an approximate performance metrics of an analytical model of access success-probability and average access delay of RA in NB-IoT. The second solution is a joint optimization of multiple parameters such as the maximum number of preamble transmissions, size of back-off windows, and the number of subcarriers per coverage enhancement level of RA to maximize the probability of successful access under a delay constraint. The accuracy of the optimization validated in computer simulations has been benchmarked in exhaustive search. However, the authors have not considered the limit of the feasibility of the thorough search method in a real-world system. But instead, they have used a proficient simulation tool to benchmark their work to promote the findings of their research work towards improving the NB-IoT RAP technology. Besides, RA performance in the higher CE level has not been considered. The research work of [95] presents an efficient 3GPP open-source simulator tool capable of investigating and modeling the behavior of RAP in NB-IoT technology. The authors explain three aspects of the usefulness of the simulation tool as; i) for analytical modeling of RAP in estimating the number of users operating RAP and an extensive study of the average end-to-end delay, ii) achieving both collision and success-probabilities incorporated into the RAP and finally, for cross-validation of the analytical model and simulation tool taking into consideration the enabling periodic report of the device referencing application networks. The research work enhances RAP optimization in the simulation tool for the standard procedure. The result achieved from the simulation tool proves the accuracy and usefulness of the calibrated tool for future activities. In summary, since the focus of all the research works is either on access delay, detection of RA preambles or optimization of resource allocation, a proficient simulation tool that captures all the limits will aid a novel NB-IoT RAP technology development.

D. CHANNEL ESTIMATION AND ERROR CORRECTION

The NB-IoT system depends on the cell-specific reference signals for channel estimation. Therefore, fast synchronization time depends on the complexity ability of the UE to assess the quality of the channel estimation. Also, the coverage enhancement of signal repetitions in exceedingly poor radio conditions, and adequate receiver performance depends on the quality of the channel estimation. The effect of poor channel estimation on NB-IoT systems can lead to passive inter-modulation, signal misdetection, carrier frequency offset, phase noise, IQ-imbalance, increased power use, and so on, to mention few. Hence, for an effective 5G NB-IoT system, the quality of channel estimation should solely depend on the user-specific demodulation reference signals [96]. Some of the solutions to poor channel estimation, as well as the error correction in the NB-IoT system in the literature are reviewed below.

In [97], the authors use a simple DFT-based low-complexity cell ID estimator to prove the estimated maximum likelihood (ML) of the cell ID in the NB-IoT system. The likelihood function was further introduced to estimate the channel leading to the maximized concentrated-likelihood function. The simulation results show a lossless performance of the exhaustive ML cell ID search as compared to the exhaustive search. Furthermore, other series of simulations have revealed a robust residual frequency offset of $\leq$ 0.5dB loss of up to 200Hz offset and a mean square error (MSE) of channel estimation of Cramer-Rao bound (CRB). However, the study has increased the computational complexity of the ML estimator which might take time and more resources to execute since NB-IoT operating SNR is expected to be less than or equal to zero. Therefore, any channel estimation and error correction algorithm should be computationally efficient at extremely low SNR. In [98], a modified linear minimum mean square error (LMMSE) channel estimation for the NB-IoT downlink system is proposed. Both singular value decomposition (SVD) and overlap banded technique have been used to reduce the LMMSE estimation complexity from the partition of the channel autocorrelation matrix into small submatrices. The performance and complexity of the LMMSE estimator have been compared with the traditional LMMSE and its counterparts. The result shows that the LMMSE estimator is useful for NB-IoT downlink systems with a dint performance of negligible degradation. However, the model is only efficient for linear data but not suitable for noisy or nonlinear data. In [99], two efficient narrowband demodulation reference signal (NDMRS)-assisted channel estimation algorithms have been proposed. The NDMRS algorithms are based on the conventional least-squared (LS) [100], and minimum means square error (MMSE) [101] methods. The results of the theoretical analysis and link-level performance illustrate that the proposed algorithms perform much better than the traditional LS and MMSE methods in low SNR conditions. Besides, analyses of raised cosine (RC) and square root raised cosine (RRC) pulse shaping for peak-to-average power ratio (PAPR) reduction have been evaluated for both single-tone and multitone transmissions for the uplink filter. The result illustrates that RRC pulse shaping with lower PAPR values can achieve a practical NB-IoT uplink transmitter design with increased power efficiency. However, the algorithms have not considered carrier frequency offset which may affect system performance.

E. CHANNEL INTERFERENCE

In the context of 5G NB-IoT, the interference is an intrinsic limitation of the NB-IoT network operating frequency reuse of the new 5G NR and 4G LTE wireless systems, although the concept of frequency reuse improves maximum spectrum utilization but at the same time limits the spectral efficiency, network and user performance. Therefore, mitigating the co-channel interference is obviously needed for the coexistence of harmonic and adaptability among NB-IoT and 5G systems. Most importantly, overcoming the interference will ensure high capacity and wide coverage of high end-user data rates as well as efficient and robust communication. The channel interference occurs in two modes of NB-IoT deployment in the 5G NR/LTE spectrum, namely, the in-band and the guard modes. The interference is termed narrowband interference (NBI) because NB-IoT bandwidth is relatively small compared with the 5G NR/LTE bandwidth. However, several factors might cause interference as a result of NB-IoT reusing NR/LTE spectrum, thus leading to problems such as the mismatch of sampling rate, power leakage between NB-IoT and NR/LTE PRBs. Loss of orthogonality is proposed in [102] which leads to performance degradation. The interference issue in 5G NB-IoT is still an open issue as adequate literature is not yet available. Most interference elimination (mitigation) methods reviewed in the literature are as follows. In [103], the authors propose a new sparse machine learning-based probabilistic structure and a sparse combinatorial optimization problem for the reliable restoration of NBI for harmonious coexistence of NB-IoT and LTE systems. The proposed algorithms are referred to as sparse cross-entropy minimization (SCEM). Further enhancement of the recovery accuracy and convergence rate has resulted in regularization in the loss function of the algorithms to produce a regularized SCEM. The simulated results outperform the state-of-the-art compressed sensing theory-based methods [104] in spectrum efficiency, estimation accuracy, computational complexity and effective elimination of NBI from the LTE systems. However, there is a tradeoff between the computational complexity and the total number of iterations which results in delays and less convergence. In [105], the block sparse Bayesian learning (BSBL) is proposed to estimate the NBI in the LTE-A systems. The estimation is aided with the use of intrablock correlation (IBC) which facilitates the recovery. Furthermore, the accuracy of the approximation technique has improved with the exploitation of the informative BSBL (I-BSBL) method using the inherent structure of the identical IBC matrix. The I-BSBL does not require prior estimation knowledge of the block partition to improve the technical performance, irrespective of the frequency offset value. The results achieved illustrate that the proposed BSBL-based algorithms achieve much more robust and accurate recovery in terms of computational and time complexity when analyzed in comparison with other counterpart techniques. However, the authors have been unable to establish the theoretical relationship between the total iteration number and the sparsity level. More importantly, the research work did not highlight the defect of the technique when the halting condition of BSBL iterations goes beyond the set threshold of the iterations. Table 5 tabulates the other common interference mitigation schemes and their objectives.

In general, since NB-IoT is part of the 5G RAN technology, the design, and implementation of an effective channel interference mitigation scheme will depend on the use cases, the scenario of its deployment and size of the cooperative set, unlike the LTE interference mitigation scheme, while sustaining an intelligent level of flexibility for the resource planning.

F. RADIO RESOURCE MANAGEMENT (RRM)

For NB-IoT to coexist within the 5G NR, the RRM strategy demands an extra degree of flexibility to introduce new functionalities, thereby enhancing QoS requirements and classifications. The allocation of radio transmission resources is among the most vital tasks of RRM to ensure massive connectivity in NB-IoT cells. Radio resources such as tone allocation, power configuration, OFDMA symbols, slots (subframes) in the time domain, the control of assignment of UL and DL resources in terms of PRBs in the frequency domain, and so on, are scheduled to support the diverse traffic

TABLE 5. Common interference mitigation schemes and their objectives

Ref.	Techniques	Objectives
E. Pateromichelakis *et al.* [106]	Centralized scheduling, as well as inter-cell interference coordination (ICIC), introduced in LTE Release 8	Enhance cell-edge SINR via frequency and power-allocation, coupled with changing levels of network coordination
E. Hossain *et al.* [107], R. Madan *et al.* [108]	Enhanced ICIC (eICIC) structure for heterogeneous networks for later LTE Releases	Providing the capacity to mitigate interference on data and control channels in frequency-domain or time-domain
3GPP TS 36.300 [109]	Further enhanced ICIC (FeICIC) from Release 11	Focuses on mitigating interference on UE via interference removal schemes.
3GPP TR 36.819 [110]	Carrier aggregation methods	Creating a degree of freedom exploited for interference management by partly avoiding interference through control-channel. scheduling of macro-cells and small cells on diverse carriers in the frequency-domain.

and latency requirements of different use cases, to ensure flexibility and maximum performance in the timing of scheduled resources. One prime challenge faced is to balance these resources among different transmission types such as unicast, multicast and broadcast, as well as scheduled and non-scheduled UL access, UE categories and related constraints such as the maximum supported data rate and supported format types. To support the traffic from both UL and DL, review of existing literature has shown a tradeoff between scheduling users, to maximize their spectral efficiency, coverage, latency or reliability [111]. This prompts the demand for a flexible and functional scheduler capable of scheduling each user to their desired optimized target. The current opinion to solve this problem is to set up a flexible design frame structure of NB-IoT in 5G NR with different transmission time intervals (TTI) and size configurations per user to aid scheduling requests. 5G NR can support single or multiple scheduling request configurations that provide gNB with information about the data and data type awaiting transmission in the device [58], [112]. The research work of [113], understands the in-applicability of the existing RRM after the introduction of the concepts of time offset and repetition to reduce the computational complexity and to provide coverage extension in NB-IoT. The authors, therefore, have proposed a theoretical structure for the upper-bound to realize a maximum data rate of 89.2kbps and 92kbps for DL and UL respectively in the proximity of a repetition factor and control channel. Secondly, a formulated interference-aware resource allocation for the maximum puzzle, studying the overhead of control channels, repetition factor and time offset has been proposed for NB-IoT using a suboptimal clarification with an iterative algorithm based on cooperative methods. The evaluation of the algorithms based on the influence of the time offset, repetition factor and intercell interference (ICI) on the NB-IoT data rate, and the energy dissipated has been studied and compared to noncooperative and optimal designs. The simulated result of the algorithm shows an 8% growth rate in the cooperative scheme and a 17% decrease in energy expended as correlated to the non-cooperative scheme. The authors in [114] have highlighted some major RRM issues affecting maximization of spectral efficiency and device connectivity between UL and DL which result in under-utilization of resources, particularly for asymmetric traffic distribution. Concern has also been raised about NB-IoT performance due to interference from multi-tier 5G HetNets. The issues raised in this article have been addressed by the presence of a novel RRM framework designed specifically for an NB-IoT-efficient resource allocation scheme through exploited cooperative interference prediction (CIP) and flexible duplexing techniques. The simulated results illustrate that the intended structure extenuates the ICI effect considerably, decreases retransmissions, supports asymmetric traffic, and enhances the overall spectrum resource utilization by up to 14% data rate, and decreases resource wastage by 58%. However, most of the RRM schemes presented in the literature have not taken into consideration the dynamism of 5G NR scheduling strategies. Therefore, for efficient NB-IoT network operability within the NR, every feature of the 5G radio access technology (RAT) needs to be evaluated for efficient adoption of NB-IoT within the networks.

G. COVERAGE ENHANCEMENT

The 5G NB-IoT design supports coverage extension of up to 164dB MCL, by enhancing cellular IoT services, most in the very hard-to-reach areas. This coverage extension demands more resources to send a data packet. For instance, data packets of 190,000 and more transmitted are in the normal CE (i.e. CE 0), while 2,606 packets transmitted are in the extreme CE (i.e. CE 2) [86]. The variation in transmitted packets creates an imbalanced use of resources in the downlink and uplink that leads to wasted resources in the uplink (i.e. in NPUSCH) and an increased latency in data transmission. To meet the coverage enhancement, three (3) solutions are proposed for NB-IoT in the literature, namely: tones (subcarriers) to minimize the bandwidth and to allocate resources instead of resource-blocks (RBs). A considerable tone number facilitates the UE to send in a narrower bandwidth. The second extract employs *repetition,* a technique used in re-transmitting data repeatedly for multiple times. The last selection is the *modulation and coding scheme,* commonly used in LTE for better coverage enhancement as considered in many research works reviewed.

The research of [115] proposes a coverage class adaptation scheme to improve the efficiency of the NB-IoT network by changing the coverage class dynamically according to the location or the state of the device channel. The result of the simulation shows a decrease in both the overhead signaling and the decoding error rate of the PDCCH, compared with the conventional coverage class adaptation scheme in the 3GPP standard. The author in [116] has employed a satellite network (i.e. LEO constellation) to study the coverage enhancement through the proposed specific unidirectional system. The model derivations demonstrate that NB-IoT can still operate within the 3GPP release 13 standard and reach 20dB MCL more than the LTE. The result shows the distortion in the packet error rate (PER) of the transmitting signal by Doppler spread. The shortcoming lies in the absence of synchronization between the NB-IoT device and the satellite which resultsd in performance degradation. More importantly, the author has not included the study of the maximum achievable throughput of the proposed system when compared with the terrestrially deployed NB-IoT. In [117], the author suggests an optimal hybrid link adaptation strategy based on repetition, bandwidth, and modulation and the coding scheme to enhance the coverage capacity of NB-IoT by using an NS-3 simulator. The implementation involves optimized problem formulation with an objective function based on the latency, and constrained-based signal-to-noise ratio (SNR). The best optimized latency algorithm with accuracy and speed deployed has been implemented for the hybrid link adaption. The numerical results show that the hybrid link adaptation is eight times faster than the exhaustive search approach with the same latency. The coverage range of 40km for open areas with better scalability is also achieved. The weakness of the research work is shown in urban areas where the reduction achieved in the packet error rate occurs at a coverage range of 2km.

In summary, signal repetition is an essential concept in NB-IoT coverage analysis that improves the coverage area but reduces the operational bandwidth. This method also reduces the amount of battery power used and the user's throughput.

H. LINK ADAPTATION

The link adaptation is an essential technology for the 5G NB-IoT system, employed for securing the reliability of transmission, coverage enhancement, peak data rate, and throughput enhancement. At NP-USCH transmission, there is an intimate relationship between power control and link adaptation (rate control), since the required received power is directly dependent on the data rate. Therefore, the proper determination of channel state information by the device and the modeling of different degrees of control channel (CCH) overhead (such as aggregation levels or several resource element dedications to CCH) based on the UE radio conditions depends on the use of scheduling grant and link adaptation [118]. Link adaptation is implemented in at least two areas, namely selection of MCS and determination of repetition. The combination of both parameters is crucial in a specific channel status. However, the sequence of both parameters can be defaced with reduced spectral efficiency and broader consumption of power if the packet size is large, notably, for inner-loop link adaptation designed to contend with block-error rate (BLER) variation and the outer loop link adaptation for regulating the selection of MCS and determination of repetition. A lot of solutions have been proffered in the literature to address these issues as compiled below.

In [119], a modest and effective link-adaptation scheme for the combination of the MCS level and the number of resource units (RU) is proposed for selecting a large transport block per packet size. The process is aimed at reducing the NP-USCH and NP-DCCH transmissions and at satisfying the BLER condition for the selected repetition number per channel status. The results demonstrate a decrease of 27% in power consumption and improvement of 69% in spectral efficiency as compared with the straightforward method. However, the authors do not define the method used for the selection of MCS and the number of repetitions for coverage enhancement. In [120], an innovative UL adaptation design with a focus on the number of repetitions is achieved by using the inner-loop link adaptation and the outer-loop link adaptation respectively. Apart from the key technologies of UL scheduling, power control and transmission gap are interpreted and a modest single-tone scheduling scheme is proposed. The link level simulation results show that the proposed UL link adaptation system exceeds the repetition-dominated approach and the straightforward approach, most notably for vigorous channel conditions and more substantial packet sizes. The proposed method preserves more than 14% and 46% of the active time and resource consumption as compared with the repetition-dominated method and straightforward method, respectively. However, the author's conclusion has not estimated the performance of the algorithms when the empirical value of the threshold exceeds the set values.

I. ENERGY MANAGEMENT

For NB-IoT, one of the enablers for rapid data traffic growth is the increase in energy efficiency. There are two energy-saving mechanisms in the NB-IoT network for decreasing the energy used by UE, namely the power-saving mode (PSM) and extended discontinuous reception (eDRX). Both mechanisms turn off their radio modules to conserve battery power, but the inability to reach these UEs while asleep may impede the use of these two mechanisms in some applications, depending on the device reachability and power consumption [121]. However, due to the latency and energy efficiency specifications of different IoT devices, new demand in 5G NB-IoT might raise the need for diverse and more efficient approaches. In the literature, different possible solutions have been proffered to solve this problem. [122] propose an enhanced energy-efficient NB-IoT system using a framework of joint optimized power ramping and preamble picking. The algorithm examines the drawback of the random-access procedure by establishing an energy estimation model that shows the impacts of the framework (power ramping and preamble picking) on energy efficiency. Besides, to reduce the complexity of the algorithm, a proposed distributed multi-agent reinforcement learning (MARL) algorithm based on ''Win and Learn'' fast policy hill-climbing (WoLF-PHC) has been used to search for optimal policies for the formulated joint optimization. The result confirms that the high energy efficiency is appropriate and convergent. However, the algorithm adaptability is not guaranteed as it takes a long time to execute and converge due to the state of parameters used in the algorithms. More importantly, the power ramping in the algorithm can be wasteful for sparse traffic. In [123], a stochastic resonance (SR) with a comparatively weak sensitivity has been merged with the Okumura-Hata model to enhance the coverage of NB-IoT base station, as well as reduce the power consumed at the terminal without modifying the cell coverage area. The proposed model validates the theoretical analysis and simulation results by efficiently diminishing the power dissipated at the terminal and improving the base station coverage area. However, the effect of different geographic (both location and environment) has a striking impact on the accuracy of the result achieved from the proposed model. In [124], a cooperative relaying paradigm is proposed to express an optimal relay selection algorithm to minimize the overall quantity of energy dissipated in NB-IoT cells. The simulation result demonstrates an energy saving of up to 30% for conventional communication techniques. Also, a greedy approach has been implemented to assist in solving the high computational effort which achieved a 10% energy consumption compared to the optimal strategy. However, the approach does not consider the impact of data rate on the algorithm since the power received is directly dependent on the data rate.

J. MODELING AND ANALYSIS APPROACH OF NB-IoT

The primary challenge of NB-IoT development is the realized network complexity and PHY-MAC layer in its system architecture. The NB-IoT network interface, radio technologies, and the modes deployed for various applications have led to the modeling issue faced. At present, there is no available methodology pattern for modeling NB-IoT complex systems. Therefore, modeling of NB-IoT systems for the three modes is a very challenging issue. These models vary from the UE differentiation performance by adjusting the physical channel deportments and network procedures in accordance with the deployment conditions, the repetition exploitation and narrowband transmission to the access of the devices in a challenging situation, to the enhanced power-saving mechanisms to increase the battery lifespan, the hardware and procedure simplification to scale down the UE complexity [87], [125].

A fascinating addition to theoretical modeling of NB-IoT based on UE's buffer has been presented as a First-In-First-Out (FIFO) queue in [127]. The research work uses a Markov-chain to model the re-transmission created by the collisions and the period of the queue and explores the three probabilities in the steady-state distribution characteristics. The analysis of the model based on the random-access performance calculated, shows the system throughput in terms of UE number, packet generation rate, retransmission number, and the period of the queue. In [126], QoS metrics such as the packet delivery ratio (PDR), throughput, and transmission time, as well as the UE configuration are proposed to meet strict NB-IoT requirements using the NB-IoT deterministic link adaptation model (NB-DLAM). The analysis of the result shows that NB-DLAM estimation on PDR is the most accurate when compared to NS-3 simulations. The NB-IoT design is aimed at reducing cost and gain power efficiency through the battery as the network scalability accommodates a large volume of NB-IoT devices with low data transmission. Again, some other model on coverage enhancement has also been reviewed. The research work of [127], models the channel estimator for two extreme channel conditions in a weak coverage environment. The signal repetitions boosting the received signal quality are affected by the quality of the channel estimation, and are limited by the channel coherence time. The author analyses the impact of channel coherence time on the uplink coverage. The result of this model illustrates that a short channel coherence time significantly reduces the amount of coverage improvement expected from the signal repetitions. All the above models did not offer a robust model that employed t*ones, repetition and MCS* implemented to support QoS performance, as well as reduce resource consumption and cost. These parameters have a direct impact on QoS metrics, including packet delivery ratio (PDR), throughput and transmission time. Therefore, these models do not represent the ideal network operation of the NB-IoT network.

K. SIMULATION AND EVALUATION

Simulation approaches are essential for robust implementation and effective deployment of the NB-IoT system [128]. Since the introduction of NB-IoT in 3GPP rel. 13, NB-IoT has become a focus of research by industries and academia. The advantages of NB-IoT in the development and implementation of IoT are numerous. The NB-IoT deployed, from the field of industrial, consumer, and enterprise IoT such as maritime, healthcare, smart environment [129], and so on have made it possible to manage an entire lifecycle of manufactured household appliances, logistics, warehousing, industrial equipment and environment for retailing applications and maintenance [25]. However, the challenges of running simulation models that bring optimization of NB-IoT superiority in the areas of long battery life, low cost, large capacity, and wide coverage into a single reality are still mostly unresolved. Several research algorithms and protocols have been implemented in the literature to improve NB-IoT performance, but none have been able to address all the listed challenges in a single model. The research work of [130], has a receiver algorithm for NB-IoT NP-RACH detection and the arrival time of estimation. The result of the simulation highlighted the potentials of NB-IoT in detection rate, false alarm, and estimated arrival time accuracy. This result does not provide an insight into ways of achieving the low-cost characteristics of NB-IoT. Another algorithm proposes the use of agent-based modeling and simulation [131] to analyze the performance of IoT systems. The algorithm uses an agent-based cooperative smart object (ACOSO) framework and OMNeT++ simulator for driving IoT systems design and deployment. The limitation of the approach lies in its unsuitability for NB-IoT modeling as it does not deal with device density, physical network design and coverage overlap. The recent simulation tools such as OPNET, NS-3, OMNeT and MATLAB are employed in [117], [126], [128], and [132] to understand and model the NB-IoT network. However, simulation tools that would validate design choices and disclose unexpected behaviors before actual system deployment are still missing. Therefore, there is no suitable simulator capable of exploring the complex evolution of NB-IoT. Table 6 tabulates the other simulation tools and modelling techniques used for LPWAN-IoT.

TABLE 6. Simulation tools used in modeling IoT networks

Ref.	Uses	Limitation
MASON [133]	Allows simulating moving entities	Does not allow consideration of high levels of details due to its nature.
SUMO [134]	Allows simulating moving entities	Requires a large amount of hardware memory.
Cooperative differential game theory [135] and Evolutionary-game theory.	Adopted for efficient energy and optimal regulation of other resources.	It is time-consuming, and the complexity and heterogeneity of IoT scenarios were not captured
IoTSim [136]	Supports and enables simulation of batch-processing activity in IoT systems limiting themselves to the MR model	Insufficient in the context of modeling and simulating the behavior of IoT complex system, which requires multiple big data programming models and diverse resources.
CloudSim [137]	Provides computing, storage, and software for hosting infrastructure-based application systems.	Creates inadequate links between datacenters, resulting in lack of exchange of shared communication

Summary: This section has highlighted the technical part of PHY/MAC performance properties of NB-IoT with the focus on improving these properties towards 5G NR compatibility with NB-IoT. Besides, we hope the anticipated 5G NB-IoT will be scalable and configurable to sustain a considerable set of distinct use cases with the following listed standards in mind.

1. Creating integrated different radio access technologies (RATs), most notably for NB-IoT and 5G coexistence to offer broad IoT services to different use cases,
2. A flexible and versatile 5G NB-IoT satisfying the required substantial heterogeneity of IoT services in different deployment modes, link requirement characteristics, and within the different carrier frequency operations.
3. Deploying QoS satisfactorily to all IoT use cases and without all interference limitations such as phase noise and channel errors.
4. Providing efficiency and robustness in energy consumption, resource utilization, cost reduction (both of hardware and software), spectral usage, and support of any future compatibility of new services and functionalities without calling for restructuring of the air interface.

IX. ENABLING MARKET FOR NB-IoT

The NB-IoT market size is valued globally at USD 578.0 million in 2018, with an expected increase of compound annual growth rate (CAGR) of 34.9% from 2019 to 2025 [138]. NB-IoT has been found to be more desirable than other LPWA technologies in the current IoT market due to its features such as the ubiquitous wide coverage area, low power usage with a promise of ten (10) years battery life, maximum coupling, low cost, high reliability, with specific carrier network security, an integrated business control platform that allows accelerated network upgrade and minimizes operational and maintenance (O&M) costs. These features have catered for the deficiencies of poor reliability, hapless security, high cost of O&M, and limited coverage area plaquing the LPWA market for over 10 years. The NB-IoT use cases and applications have controlled the IoT market due to the dramatic growth in the scope of internet usage from people-operated computers to autonomous smart devices. Thereby promoting industry players' participation in NB-IoT exploitation. The increase in internet usage has created innovative IoT services and hardware that generate revenue through the possible diagnostics, control and monitoring of connected devices in remote areas (or far from the reach of the cellular base station) by saving the cost of operation and maintenance [139]. The NB-IoT global market is segmented into five sections to dissect the grand-view research analysis of the market. The segmented parts are; NB-IoT component, deployment, device type, applications (end-uses) and regions [140]. These analyses will expatiate the targeted niche markets of NB-IoT and its competitive landscape for market leaders.

The segmentation by component can further be sectioned into the network and the module sections. The network section promotes cost-effective services that increase the number of IoT deployments while the module section is predicted to rise the demand of NB-IoT modules for specific consumer-oriented applications. The NB-IoT deployment segment defines the modes (i.e. in-band, guard band, and standalone) that have been adopted the most. The most adopted mode in 2018 was the guard band, owing to its deployment in the existing cellular network, including radio frequency (RF) and antenna without any spectrum cost appended. It is predicted to be the driving factor behind the growth of NB-IoT in the guard band section.

The segmentation by device type sectioned the market further into devices that measure specific parameters such as smart meter, alarm and detector, wearables, and many others. The wearable-device categories controlled the market in 2018 due to the rapid increase in demand for personal care devices and diagnostics such as the sport, healthcare, and fitness devices.

The application section deals with the sectors of the industries that employ NB-IoT technology, for example the automobile, and agricultural industries, healthcare, infrastructures, energy and utilities, manufacturing, consumer electronics, and many others. The consumer electronics section is expected to control the market due to the NB-IoT module's integration into consumer products such as wearables, phones, home electronics, and so on. An example is a case in Germany, where Vodafone and Panasonic Corporation collaborated to manufacture an electronic device for home-based appliances that will enable consumers to store data related to all electronic devices on the cloud.

And finally, the region section represents the largest market of NB-IoT technology. North America's reported domination of the market in 2018 was due to the presence of leading device manufacturing companies and network service providers such as Qualcomm Inc., AT&T, Cellco partnership, MediaTek, and so on. These companies focus on testing and commercially deploying NB-IoT solutions for both consumer and industrial applications. [138].

A. 5G NB-IoT USE CASES AND APPLICATIONS

NB-IoT supports the achievement and aspirations of diverse use cases and applications without human intervention. These applications enhance lives and daily activities. The three groups of use-cases of NB-IoT are the consumer IoT, industrial IoT, and enterprise IoT, as sketched in Figure 9. The consumer IoT involves smart homes, environmental surveillance and smart offices and many others. The industrial IoT involves smart factories, agricultural surveillance (e.g animal tracking, and so on). The last group is the enterprise IoT consisting of the smart city and all public utilities (such as energy plant and management, and so on). Table 7 tabulates the benefits of NB-IoT in each use case and the possible key challenges to be addressed in 5G NB-IoT.

The objective of 5G NB-IoT is to offer an integrated experience for users deploying the different use cases listed above. Each of the use cases is anticipated to have a comprehensive specification from the network operations. However, the successful deployment of these use cases on the 5G NB-IoT network using sensors will support the growth and improvement of IoT services in the vertical industries, and for social-economic benefits. The improvement in IoT services will provide more business opportunities for NB-IoT network operators.

X. OPEN RESEARCH CHALLENGES AND DISCUSSION

This section summaries the open challenges on NB-IoT system interoperability and coexistence within 5G NR carriers. The open research challenges need to be resolved to support multiple use cases that are coexisting with the 5G NR air interface.

A. PHY/MAC DESIGN CHALLENGES FOR NB-IoT IN 5G NR

1) HYBRID AUTOMATIC REPEAT REQUEST (HARQ)

Fading causes variation of signal strength at the receiver, leading to a data loss in most wireless channels. To increase the reliability of the data transmission link in NB-IoT, the HARQ mechanism is used as one of the potent technologies to achieve super coverage with low complexity. NB-IoT adopted a single-process adaptive and asynchronous HARQ for both UL and DL just as in the 5G NR wireless system. NB-IoT uses the HARQ type II due to its soft sequence increment at the

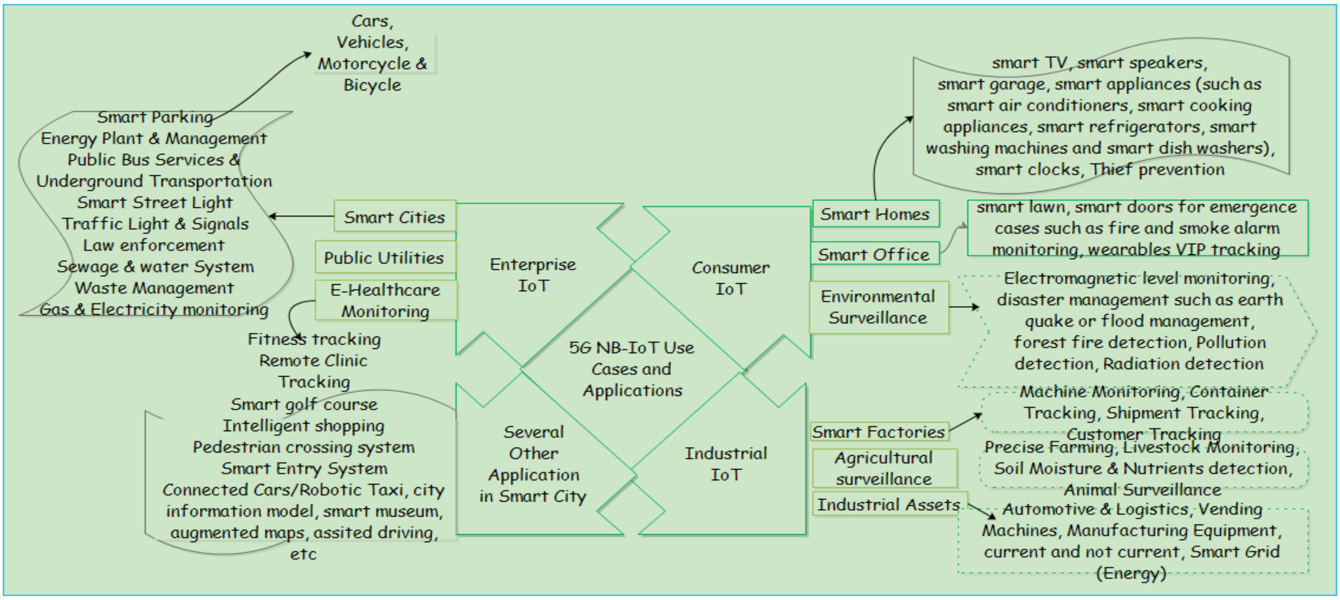

FIGURE 9. Classification of 5G NB-IoT Use Cases.

receiver to raise error corrections. This mechanism consumes more transmit power during the process of retransmission, rises packet drop probability, doubles the cost of processing effort, and overhead that increases the latency. Therefore, for an effective 5G NB-IoT system to generate a degree of flexibility in serving various use cases and also meet the stringent latency condition for uRLLC services, a versatile air interface design and optimal resource utilization of channel resources during the transmission are desirable. The air interface should involve a flexible link layer design that creates an adaptation of every single link in logical terms with its QoS requirements and the received radio considerations. Also, the advancement in the HARQ mechanism should enhance the timing design for scheduling over asymmetric DL and UL transmission in 5G NB-IoT cell scenarios depending on the TTI size used for diverse use cases. As proposed by [141], enhanced HARQ feedback can be used for improved network-based interference coordination to improve the success rate of HARQ retransmission.

2) ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM) WAVEFORM LIMITATION

The most salient multicarrier waveform representation in NB-IoT is OFDM. This allows high spectra efficiency due to the maximum usage of the bandwidth by the subcarrier signals. Though the orthogonal design of these spectra ensures free interference reconstruction at the receiver. However, there are some drawbacks to this waveform. One major drawback is the lack of secure synchronization in time and frequency to support the signal orthogonality, as well as vulnerability to doppler distortions in highly mobile channels. The reason for this drawback is the *sinc-shape* of the subcarrier spectra that results in the poor localization of the signal power in the frequency domain due to the high side lobes. The limitation of OFDM leads to the adoption of cyclic prefix OFDM (CP-OFDM) [148] in the NR system. The CP-OFDM was created to keep the guard interval overhead small to prevent degradation of spectral efficiency However, the limitation of CP-OFDM in peak-average power ratio (PAPR), out-of-bound emission to minimize power back-off, lower frequency localization, and slacken synchronization requirements [58] renders the usage of CP-OFDM unfavorable. Moreover, other proposed waveforms of different variation of CP-OFDM (such as filter bank multicarrier (FBMC), generalized frequency division multiplexing (GFDM)) that outperform more than the CP-OFDM comes at the cost of high transceiver complexity and incompatibility with the MIMO techniques. This poses a challenge to NB-IoT due to its low complexity. Again, because of the advantages of high spectral efficiency, compatibility with MIMO and low-complexity implementation, 3GPP adopted the CP-OFDM and mitigated its challenges with well-established techniques such as filtering, clipping, and windowing. However, for better coexistence between NB-IoT and NR, a multi-carrier waveform with spectral containment of signal power, flexible and capable of asynchronous UL access and able to be evaluated with the following key performance index (KPI) (spectral efficiency, PAPR, phase noise robustness, robustness to frequency/time selective channels, MIMO compatibility, time localization, OOB (with and without PA), complexity and flexibility) is desirable.

3) PHASE NOISE

The major challenge to designing the OFDM waveform is the demonstration of imperfections in the function of the transceiver hardware used in its implementation.

TABLE 7. The benefit of NB-IoT in each use cases and possible critical challenges related to their deployment

Classification	Applications	Benefits	Challenges
Consumer IoT	Smart Homes	-Promote the growth of the use of voice-assisted devices in our homes. -Provide a centralized platform for solving many challenges related to home appliances [44]	1. Might be prone to a series of attacks due to a single layer of management level, i.e. the centralized system adopted. Therefore, formalized encryption mechanism is needed to secure the NB-IoT communication Network.
	Smart Offices	-Help in organizing office calendars, utilities billing and consumption, entry, and security systems through the data collated. -Aid the use of cognitive NB-IoT for personalized and tailored home and office environments for advice about office activities such as workout, weather control, traffic conditions, predictive maintenance, alerts, etc [44].	
	Environmental surveillance	-It helps to create an enabling environment that saves time and cost thereby increasing the productivity. - Can be used for detecting natural disasters such as earthquake, landslides, etc. -Use for tracking ambient temperature, humidity, rainfall, and air quality through NB-IoT sensors [142]. -Help in monitoring public waterways, parks, and green spaces in order to identify spaces that require clean-up or projection [44].	2. Accuracy and reliability of data collection might be greatly affected due to interference and the kind of sensors deployed. Also, the inadequacy of manpower and training can hinder the effectiveness of the system.
Industrial IoT	Smart Factories	-The use of networked NB-IoT sensors on smart machines and analytical data can enhance the day-to-day business across a wide range of market sector and activities from manufacturing to public services. -it can be used for application monitoring, monitoring of chemical production plant processes, monitoring of vehicle fleet, etc. thereby enhancing optimal planning and flexibility in manufacturing and maintenance. - can be used to create industrial automation by providing a model for connection of industrial IoT devices to the critical industrial systems. This will minimize factory downtime and create scheduling maintenance [43].	3. Fault identification and possible repairs can be a serious issue in large NB-IoT network. Since there can be limitation in IoT devices and also, environmental factors are inevitable. Interoperability issues, positioning accuracy, and management of open data can also be a problem.
	Agricultural surveillance	-For surveillance monitoring of domestic animals and Livestock. - For monitoring of weather conditions such as temperature, humidity, soil moisture and nutrients, etc - Can be used for smart green houses and for enhancing the sales of agricultural products. - can ensure consistent conditions of the grower and improve productivity. - Can be used in Geo-fencing and Chrono-fencing of livestock [143] - Can be used to provide information about certain parameters when they exceed the threshold while maintaining the trend of data analysis [43],[142].	4. The limitation in the UE complexity, positioning accuracy, and calibration of hospital wearable devices can lead to misinformation and wrong diagnosis in inpatient treatment.
	Industrial Assets	- The combination of NB-IoT network and AI can be used to create an alert for automatic monitoring machine conditions. - Can be used for logistic and industrial assets tracking - can be used for monitoring equipment status, control processes, and safety in the factory [43].	5. Several cyber-attacks might be launched on the NB-IoT Industrial assets networks due to the signal traveled distance, correlated related-critical areas and low complexity of NB-IoT devices which cannot be used to run complex algorithms.
Enterprise IoT	Smart City:	-Promote the implementation of smart applications. - Assist fostering of a data-driven economy - Benefit the government/tourists/residents with a huge amount of structured and un-structured data that can be used for automation, decision-making and analysis. - Promotes cognitive computing in citizen centric - Provides cross-collaborations and application opportunities to citizens to engage with LG, communicate requests, feedback or reports faults with utilities and infrastructures [44].	6. The security and privacy protection of data generated from the NB-IoT use cases is not guaranteed as some of these data might be life threatened to the organization that adopted the NB-IoT networks if proper authentication is not implemented. Example is the medical data related to the security of patient's life.
	Smart Parking	-It improves efficiency, cost, effort and fuel consumption and time in trying to search for parking space near/at any destination. - can use NB-IoT devices with Ultrasonic sensors detecting the availability of a parking space - Helps the driver to book for a parking spot upfront or proceed directly to the vacant spot. - Provides parking information on the driver dashboard, guiding the driver to park at the exact location of the vacant spot at his destination. - Generates income for the government based on the charge calculated for amount of time spent on the reservation. - Helps parking officers to use the parking information to manage and handle billing information better and also offers discounts based on the parking utilization and several other analytic tasks [44].	7. Poor and inefficient NB-IoT network design can lead to hugh amount of energy consumption by the sensors, data overload, and heterogeneity of data during communication, if the implemented protocols are not energy efficient. Also, the lack of data fusion suitable for NB-
	Smart Street Light	-It can be used to enhance energy utilization and improve the management of the large-scale deployment of streetlights, thereby reducing the difficulty in their maintenance. -It can foster the adoption of an intelligent energy consumption model for massive urban street light control and real-time status monitoring of the streetlights. - Fosters onward upgrading and performance optimization by analyzing the data collected from streetlight information [144].	

TABLE 7. *(Continued.)* **The benefit of NB-IoT in each use cases and possible critical challenges related to their deployment**

Waste Management	-Notifies and reports the level of the waste to the waste management authority [145]. - Promotes cost-effectiveness in waste collection management through fuel saving of the collection vehicle. - Ensures smart routes and is sustainability complacent [44].	IoT can lead to more consumption of energy. Therefore, a data fusion algorithm is needed to compressed the data or generated data to reduce the energy consumed. 8. To support QoS and customization of 5G NB-IoT in various use cases, the limitation in the functionality of the EPC architecture of LTE network needs to be overcome by exploiting the network enabler such as SDN, NFV, mobile edge computing and so on. 9. To avoid the plummeting of the NB-IoT modules and service solutions in 5G network, a deployment assessment detailing the sincere traffic forecast with estimated revenue, and techno-economic analysis should be documented to positioned the NB-IoT market over other LPWA devices. 10. Different access control level should be provided to users to avoid data sharing.
Gas & Electricity Metering	-Ensures more efficient electricity and gas delivery by applying analytic data to the data gathered from the smart electricity grid. - Enhances plans, project demand, and capacity byusing data gathered from the grid operators. - It can be used to provide an intelligent inter-connection and cooperation between the electric Vehicles, Batteries, and Charging stations under the control of the Power supply Grid-management System (PGMS). -It can offer low-cost energy and power consumption in hardware [44],[146].	
Public Bus services and Underground Transportation	-Help in monitoring the position of trains on routes. -Monitors the health of the tracks, bus arrivals, and departures or bus emergencies or breakdowns for effective fault detection. -Enhances the saving of lives and properties, minimizes delays and optimizes the operations [44].	
Energy Plant & Management	-Promotes a load-balancing system -Provides healthy monitoring of energy plant -Ensures adequate maintenance and fault detection.	
Sewage and Water System	-NB-IoT can be used for monitoring public sewage, waterways leakages within society.	
Shipment Tracking	-It can be used for tracking goods, rentals, cargo locations, Storage capability etc.	
Smart Clinic/Hospital	-It can be used to collect data in real-time of various health conditions of patients ranging from heart rate, body temperature, etc. through wearable devices. -It can provide comprehensive information about outpatient medical records to the doctors based on the data collated from the wearable devices. -It can be applied to supervised a discharged Patient's health condition (PHC) through wearable devices [147].	

The variation in phases between the receiver and transmitter oscillators due to the discontinuously received coded repetition transmit data blocks, causes the presence of random phase noises in the signals received. The imperfections become more disturbing in the higher-level carrier frequencies. The most common hardware impairment is the oscillator phase noise, and nonlinear characteristics of the power amplifier. The most prominent of all is the phase noise phase locked-based oscillator that contains three (3) sources of noise namely; the reference oscillator, the phase frequency detector along the loop filter, as well as the voltage-controlled oscillator (VCO). Each of the sources of noise contains both thermal noise (white noise) and flicker noise (colored noise). The defamatory consequence of phase noise increases with the carrier frequency function. The effect of phase noise causes common phase errors and intercarrier interference (ICI) that result in an increment of error vector magnitude (EVM) of the desired signal.

4) COEXISTENCE ISSUE

Since the adoption of CP-OFDM based waveform for eMBB services [148] by 3GPP NR, other waveforms for other services such as the NB-IoT service for mMTC have not been precluded. Therefore, the 5G NR coexistence with NB-IoT must be manageably orthogonal (or quasi-orthogonal) to reduce the mutual interference that can restrict the form of freedom in the general design of the waveform. Another constraint of 5G NR coexistence with NB-IoT is the structural design of the frame of NB-IoT. The NB-IoT NP-DCCH resides in three consecutive OFDM symbols across the whole band. Also, the relationship of cell-specific reference symbols derived from the narrowband cell identity in a specific in-band deployment is not permitted to be subdued, when NB-IoT is internetworked with the 5G NR but rather, the 5G signals are restrained at a unique location in the time-frequency grid due to their adaptability. The introduction of minislots in 5G NR can resolve the above challenge. The choice of frame design in the UL is not restricted, as the placement of both the control channel and the reference symbol is frequency-localized to avoid overlap of NR with the NB-IoT.

5) CELL SEARCH AND INITIAL SYNCHRONIZATION

There is a significant difference in the cell search and initial synchronization of 5G NR and the NB-IoT system. The difference poses a severe challenge to the 5G NR's coexistence with the NB-IoT due to the latency and signaling overhead detection. For instance, the NB-IoT cells use ungrouped NPSS and NSSS for cell search discovery. Also, NPSS does not contain physical cell identity (PCI) information as compared with the SSB block of NR that depends on the PCI. Again, the PSS and SSS in the SSB are the same and cannot determine the relative device location. Besides, NR SSB uses different m-root sequences with 20ms periodicity, which is four times higher than the 5ms frequency domain of Zadoff-chu (ZC) sequence of both NPSS and NSSS in NB-IoT. The lengthy SSB period accepts the ultralean design paradigm and supports the efficiency of the energy consumption rate of the NR network that alleviates the provision of massive access to higher loads. Therefore, to foster NR coexistence with NB-IoT, a flexible cell search discovery that would achieve a reduction in signaling overhead and latency should be proposed.

6) CONTENTION-BASED/GRANT-FREE ACCESS

The previous contention-based access protocol has been marred by high signaling overhead and high latency, which hampered the performance of the NB-IoT network due to the massive rise in the number of devices per cell. The introduction of NB-IoT technology for mMTC service support for the 5G NR technology has made 3GPP agree to extend the contention-based access used by the UEs for the initial connection to the network to RRC connected-inactive to compliment RRC-idle and RRC-connected state. The added state will support grant-free, semipersistent scheduling, and UL transmission with a grant [148]. The access scheme is required for mMTC services to maintain the large number of active UEs concurrently striving to access the network. The RRC connected-inactive will support various UE services, battery life, latency, and mobility. According to [149], three types of contention-based access protocol have been proposed to complement the RRC-idle and RRC-connected namely; a) the multistage access scheme; b) the two-stage (double) access scheme, and c). one-stage (single) access scheme.

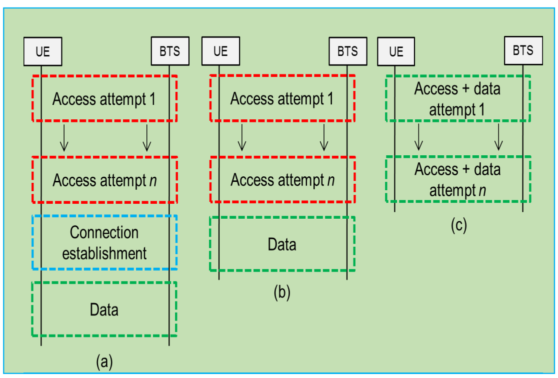

FIGURE 10. The considered contention-based access-protocol [58].

The multistage access is similar to the tropical NB-IoT link establishment which comprises three stages, namely access, link establishment (inclusion of security and authentication), and finally the data phase. The double (two-stage) access permits the UE to isolate the access-notification phase from its data delivery phase while the one-stage access uses both access notification and data delivery in one transmission as depicted in Figure 10. For both the single and the double-access schemes, contention may occur only in the initial step of the protocol. Inventing this kind of access scheme is a mutual interaction between the physical design (to enhance discovery and to manage collisions through high-level signal processing) and the higher layers (to manage network entries of the PHY capacities).

7) SEMI-PERSISTENT SCHEDULING (SPS)

The NB-IoT scheduling study of channels and signals in the literature is centered around dynamic downlink and uplink scheduling. However, most of the scheduling techniques adopted have high overhead as compared to SPS with minimal control signaling overhead suitable for traffic with periodic features such as the NB-IoT. However, SPS has few built-in inefficiencies, such as the empty transmissions for implicit release. The implementation of SPS in 5G NB-IoT would need further improvements to configuration/activation split and sharing of SPS resources to support the effective operation of NB-IoT in the 5G NR systems.

8) RANDOM ACCESS PROCEDURE (RAP)

The challenge of an insufficient number of preambles in NB-IoT RAP results in collision problems, a low random access (RA) success rate, high network congestion, and access delay if massive devices attempt to access the radio channel resources simultaneously for UL data transmission. The challenge further complicates the network so that it consumes more power, has high packet loss and excessive use of radio resources, thereby overloading the NPRACH. Many approaches proposed can be classified into two broad groups, namely the pull-based and push-based procedures. Both procedures try to solve the challenge of collision and latency requirements based on the method of groups prioritization and small-data transmission (SDT), respectively [58], [150]. However, none of the schemes is effective in meeting the challenges mentioned above. Therefore, grand-winning research is required to propose priority level-specific RACH-preambles, that permit an improvement in the success probability of the initial access of high-priority services, without decreasing the initial access of other functions [16].

9) RADIO RESOURCES MANAGEMENT (RRM)

The radio resource allocation is an essential task for RRM for varying signaling patterns amongst diverse transmission types (such as broadcast, unicast and multicast, as well as scheduled and nonscheduled UL access) in NB-IoT network. The critical issue is partitioning the available resources between the network infrastructure and UEs without resulting to intercell interference. It is predicted that the deployed NB-IoT in 5G NR carriers may lead to a new challenge of intercell interference and resource scheduling that needs to be overcome to secure flexibility, high network capacity, and broad coverage in the network.

10) INTERFERENCE MITIGATION

The deployment of NB-IoT carriers within the 5G NR carriers will result in a new interference challenge that is different from that of the legacy network, although the NR's coexistence with NB-IoT is considered to improve network capacity and expand the coverage of the user data rate, as well as improve robust communication through the process of frequency reuse. The interference challenges may hamper the channel estimation for NB-IoT devices which cripple the achievable energy performance, as well as the spectral efficiency. Therefore, an interference-mitigating scheme becomes an essential strategy in curbing this challenge. The design of 5G NR ultra-lean was implemented to improve the performance of energy, and to minimize the interference in the network, but the design alone is not enough to curb the threat of channel interference.

11) LATENCY

Low-latency support is an essential strategy for coexistence between the NR and NB-IoT systems. The latency in the NB-IoT network remains 10s, and the latency for NR is 1ms for improving the signal-to-interference-plus-noise ratio distribution among users. The increase in repetition for a device that experiences path loss, coverage class, exchange of messages for RA, control and data channels, contributes to the latency of the system. The extent of the challenge depends on the scheduling strategy of the UL and DL channels. Many approaches proposed to reduce the timing request of NB-IoT transmitting devices in LTE carriers and for minimizing the transmission latency have been suggested in the literature. However, the idea of NB-IoT deployment in NR carrier needs a different approach, considering the essentials of mini-slot (as the smallest slot) that can be scheduled to reduce latency in 5G NR.

12) ENERGY SAVING

The eDRX and PSM are the two energy-saving mechanisms employed in the NB-IoT network to extend the device battery life. Similarly, there is an inefficiency in the two popular RRC schemes adopted (i.e., RRC idle and RRC connected). The schemes result in high protocol overhead due to the transition of UE from the RRC idle to RRC connected for a device enduring bad channel conditions. The situation can worsen for a network with a massive number of devices transmitting low data frequently. Moreover, it is not cost-efficient to keep the device in the RRC connected state without any active data transmission due to the extensive consumption of battery power, high usage of dedicated resources, high measurement reports, and handovers. However, with the proposed deployment of NB-IoT in 5G NR, a new scheme has been proposed to enhance the RRC scheme. The 3GPP adopted a lightweight signaling transition from RRC connected to RRC-connected inactive [148]. The RRC-connected inactive should benefit low data transmission optimization for devices operating for a short period. The UE transmitting UL data can use the small-packet transmit procedure (SPTP) to communicate, depending on the contention-based processes adopted. The method might be a single contention-based (one step) or prefaced by a contention-based scheduling request and grant (two-step) [151]. The RRC connected-inactive has the support of the configurable DRX in the frequent monitoring of the system control channels by some devices and for others in low-activity state for many hours that could also continue connection quickly after their low-active state. Furthermore, there is still a need for further research into the proposed RRC connected-inactive due to some overhead and latency issues that may be encountered in the network. Moreover, the emerging ambient backscatter with relay cooperation technology can be incorporated into NB-IoT design to perform simultaneous wireless information and power transfer (SWIPT) mechanisms. This design can prolong the lifetime of NB-IoT devices, expand communication distances and channel capacity, and improve link reliabilities.

13) HETEROGENEITY AND INTEROPERABILITY

The interoperability of NB-IoT products from Multi-vendor is one way to standardize the future IoT-platform and applications towards mMTC services. Various NB-IoT products from leading Telecom companies such as Qualcomm, Ericsson, Nokia, Huawei, and Affirmed Networks have all pass-through interoperability development testing (IODT) carried out globally by Vodafone networks and its partners [152]. Currently, Vodafone and GSMA are preparing a roadmap for the NB-IoT scale and flexibility required to achieve numerous applications. We hope that proper documentation on usage type, product number, deployment types, adaptability and duration of the device will be specified. However, the device complexity should be upgraded to include improved latency, the accuracy of measured data, further enhanced NPRACH, improved power and some programmable chips for light algorithm support to be implemented and managed over the air (OTA) to satisfy further use cases. Also, there should be a reference standard that would serve as a guide for all the IoT platforms.

14) SECURITY AND PRIVACY

The integration of NB-IoT into the 5G NR networks will provide assumed security and privacy. The NB-IoT operation does not have any practical access-authentication scheme in 5G networks due to its low complexity as related to the 3GPP standard. NB-IoT adopts the conventional access-authentication methods to achieve mutual authentication with the network which may result in massive signaling overhead. However, this poses a severe challenge to securing NB-IoT devices. A solution from [153] guarantees the application of lattice-based homomorphic encryption technology access authentication in NB-IoT.

15) CHANNEL MODELING

The emergence of 5G NR has brought new challenges to the data rate for shared channels at diverse configurations, link reliability, end-end (E2E) latency, to the modeling of NB-IoT channel for different use cases and service types, inadequately supported by the current channel models. Channel models such as the updated 3GPP NR channel model and

IMT-2020 channel model with a wide range of frequency of 0.5MHz-100GHz [154] mmWave propagation characters such as modeling of blockage and atmospheric attenuation, high mobility, space-time-frequency consistency, dual connectivity and beam-tracking simulations, have not been tested to predict the accuracy and peculiarity of the NB-IoT propagation channel. However, the evaluation of these models has shown a deficiency in the estimation of loss in deep shadowing zones, spatial consistency procedure in the channel modeling for evaluation of user mobility, multiuser-multinode communications and beam-tracking design for 5G communication, a unification of path loss model from 0.5MHz-100GHz, link-specific outdoor-to-indoor penetration, UE-specific outdoor-to-indoor penetration, and the frequency inconsistency within the channels below and above 6GHz for dual connectivity of multiple frequency bands between the separation of the control plane and the user plane for throughput enhancement in mmWave band.

Therefore, to develop efficient 5G NB-IoT channel models to support the massive devices, channel features such as the time variability of scattering clusters, deep shadowing, dynamic blockage or movement in the dual-mobility scenarios, aerial scenarios, carrier frequency, system bandwidth, transmit power for eNB and UE, propagation model, doppler spread (for denoting speed of UE for the base station and also, due to the significant impact it has on the CP length of the OFDM symbols), antenna configuration and noise figure for UL and DL should be studied [43], [58].

B. SWOT ANALYSIS OF NB-IoT TECHNOLOGY

This segment presents a strength, weakness, opportunities, and threat (SWOT) analysis of NB-IoT technology. The main strengths of NB-IoT are low-cost devices, the mass connection of devices, ultra-low power consumption, in-depth coverage, stability, safety, and reliability to support a large number of diverse use cases. These features have made NB-IoT the choice of many organizations.

The primary weakness of NB-IoT is the inaccessibility of the downlink channel (due to the usage of PSM and eDRX), security, and scalability. However, various modifications are on-going to introduce an additional feature that would meet these challenges.

The low-power transmission synchronization and the possible multifold services are parts of the great opportunities that can be provided by NB-IoT for future IoT deployment and access to the 5G networks.

The greatest threat to NB-IoT technology is the signal interference induced by long communication distance, which is a key design challenge for the fabrication, integration, and implementation of NB-IoT devices. Poor scheduling of resource allocation can also result in interference; and large consumption of power raises the latency and increases proneness to attack by adversaries. Details of all the challenges affecting the deployment of NB-IoT have been elucidated in section 10. Table 8 presents a summary of all the SWOT analyses of NB-IoT technology.

TABLE 8. Summary of swot analyses of NB-IoT technology

Strengths	Weakness
20dB Deep-coverage area, low-cost device, ultra-low power consumption, easy to implement, cost-efficient to deploy, can be implemented on a general-purpose computing platform, Attractive to cloud computing platforms (CCP), CCP offers scalability, efficiency and possible reduction in cost for various use cases. Massive connection of devices, safe, reliable and stable for large-scale connection, licensed and secure spectrum, open standard technology, low-complexity, easy coexistence with other technologies, supported by more than 30 of the largest Telecom operators, and support access stratum optimization	-Capacity requirement -Latency can be high for a massive connection -Scheduling delay might be high - Signaling overhead can be high -Increased operational cost for massive dense IoT application deployment due to subscription fee application. -Scalability
Opportunities	**Threat**
-Reduction in low-power consumption, Growing market demand for various use cases, enabling intelligent and smart economy, environments, cities, that can be used to create jobs and increase income. The inclusion of tone, repetition, modulation, and coding, for coverage enhancement, efficient scheduling resource allocation, use of artificial intelligence, etc.	-Signal attenuation induced -Security and privacy -Out-of-bound emission (OOB) - High price

XI. CONCLUSION

Most of the previous reviews explicitly based their study of NB-IoT on the LTE system's limitations and simulations. The findings and solutions proposed by these reviews cannot be implemented for the ongoing 5G NB-IoT system. However, it has been observed that the most potent mechanisms (such as the HARQ, contention-based, radio resource management, etc.), required by the NB-IoT system to operate seamlessly, are limited in capacity and unsuitable for coexistence with the 5G NR carrier network. To build a robust, efficient and satisfactory service quality for 5G NB-IoT networks, the mechanisms of NB-IoT systems need to be researched further and enhanced. Therefore, this review provides detailed guidelines for integrating NB-IoT into 5G networks. This is the first study of the challenges and operation of NB-IoT technology for 5G NR coexistence. Based on this survey, an analytical investigation of the NB-IoT environment for a 5G-IoT class of connectivity, cloud-assisted relay with ambient backscatter communication, as well as the limitation of the inseparable control and user planes of LTE EPC posing a challenge to the performance and acceptability of LTE NB-IoT, were presented to enhance the understanding of NB-IoT performance and problems. Furthermore, the possible 5G architectural design for NB-IoT integration, technical performance, enabling markets, use cases, application and key challenges to all the use cases, as well as all the required enabling technologies needed for the optimal combination, has been introduced for the coexistence of NB-IoT with 5G NR. Finally, open research challenges and future research focus on the coexistence of 5G NR with NB-IoT have led to this SWOT analysis which is presented to foster research activities for future IoT. Some of the challenges involve channel scheduling, interference, random access procedures, heterogeneity, and interoperability, which need to be solved to promote successful NB-IoT systems. In summary, 5G NB-IoT flexibility can be achieved if all the mechanisms of 5G NR can be adapted to suit the coexistence with NB-IoT and other cellular technologies' air interface variants (AIVs), to promote the versatility of the 5G NR protocol stack as compared with that of the 4G networks.

APPENDIX

Some of the abbreviations and acronyms used are listed in the table below

ABBREVIATIONS AND ACRONYMS USED

5G-IoT	5th Generation Internet of Things
5G- MTC	5th Generation machine-type Communication
5G-NR	5th Generation New Radio
CDMA	Code Division Multiple Access
CIoT	Cellular Internet of Things
CP-OFDM	Cyclic Prefix OFDM
CRAN	Centralized/Cloud Radio Access Network
CSI	Channel State Information
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IQ	In-phase and Quadrature Phase
ISO	International Organization for Standardization
MIB	Master Information Block
NPDCCH	Narrowband Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
NPSS	Narrowband Primary Synchronization Signal
NSSS	Narrowband Secondary Synchronization Signal
NPBCH	Narrowband Physical Broadcast Channel
NPUCCH	Narrowband Physical Uplink Control Channel
NPUSCH	Narrowband Physical Uplink Shared Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NRACH	Narrowband Random-Access Channel
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDN	Software-Defined Networking
SIB	System Information Block
SINR	Signal to Interference plus Noise Ratio
SIMO	Single Input Multiple Output
SMF	Session Management Function
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal

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REFERENCES

[1] S. Li, L. D. Xu, and S. Zhao, "5G Internet of Things: A survey," *J. Ind. Inf. Integr.*, vol. 10, pp. 1–9, Jun. 2018, doi: 10.1016/j.jii.2018.01.005.

[2] I-SCOOP. (2020). *5G and IoT:The mobile Broadband future of IoT*. I-SCOOP. Accessed: Jun. 9, 2020. [Online]. Available: https://www.i-scoop.eu/internet-of-things-guide/5g-iot/

[3] 5G American. (2018). *5G Americas White Paper*. Accessed: Mar. 19, 2020. [Online]. Available: https://www.5gamericas.org/

[4] F N Division TEC. (2019). *Study Paper:5G-Key Capabilities & Applications*. Accessed: Apr. 20, 2020. [Online]. Available: https://www.scribd.com/document/429963083/5G-Study-Paper-approved-by-Sr-DDG-pdf

[5] Gartner. (2017). *'Things' Will Be in Use in 2017, Up 31 Percent From 2016*. Gartner Inc. NewsRoom. Accessed: May 20, 2020. [Online]. Available: https://www.gartner.com/en/newsroom/press-releases/2017-02-07-gartner-says-8-billion-connected-things-will-be-in-use-in-2017-up-31-percent-from-2016

[6] L. Oliveira, J. J. P. C. Rodrigues, S. A. Kozlov, R. A. L. Rabêlo, and V. H. C. de Albuquerque, "MAC layer protocols for Internet of Things: A survey," *Future Internet*, vol. 11, no. 1, p. 16, 2019, doi: 10.3390/fi11010016.

[7] B. Buurman, J. Kamruzzaman, G. Karmakar, and S. Islam, "Low-power wide-area networks: Design goals, architecture, suitability to use cases and research challenges," *IEEE Access*, vol. 8, pp. 17179–17220, 2020, doi: 10.1109/ACCESS.2020.2968057.

[8] M. Bembe, A. Abu-Mahfouz, M. Masonta, and T. Ngqondi, "A survey on low-power wide area networks for IoT applications," *Telecommun. Syst.*, vol. 71, no. 2, pp. 249–274, Jun. 2019, doi: 10.1007/s11235-019-00557-9.

[9] R. Boisguene, S.-C. Tseng, C.-W. Huang, and P. Lin, "A survey on NB-IoT downlink scheduling: Issues and potential solutions," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 547–551, doi: 10.1109/IWCMC.2017.7986344.

[10] C. B. Mwakwata, H. Malik, M. Mahtab Alam, Y. Le Moullec, S. Parand, and S. Mumtaz, "Narrowband Internet of Things (NB-IoT): From physical (PHY) and media access control (MAC) layers perspectives," *Sensors*, vol. 19, no. 11, p. 2613, Jun. 2019, doi: 10.3390/s19112613.

[11] Qualcomm. (2019). *3GPP Charts for the Next Chapter of 5G standards*. OnQ Blog. Accessed: Mar. 28, 2020. [Online]. Available: https://www.qualcomm.com/news/onq/2019/12/13/3gpp-charts-next-chapter-5g-standards

[12] M. Chen, Y. Miao, Y. Hao, and K. Hwang, "Narrow band Internet of Things," *IEEE Access*, vol. 5, pp. 20557–20577, 2017, doi: 10.1109/ACCESS.2017.2751586.

[13] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 855–873, 2nd Quart., 2017, doi: 10.1109/COMST.2017.2652320.

[14] S. Narayanan, D. Tsolkas, N. Passas, and L. Merakos, "NB-IoT: A candidate technology for massive IoT in the 5G era," in *Proc. IEEE 23rd Int. Workshop Comput. Aided Modeling Design Commun. Links Netw. (CAMAD)*, Sep. 2018, pp. 1–6, doi: 10.1109/CAMAD.2018.8514963.

[15] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-mahfouz, "A survey on 5G networks for the Internet of Things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018, doi: 10.1109/ACCESS.2017.2779844.

[16] X. Ge, Z. Li, and S. Li, "5G software defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 87–93, Jul. 2017.

[17] Y. D. Beyene, R. Jantti, O. Tirkkonen, K. Ruttik, S. Iraji, A. Larmo, T. Tirronen, and J. Torsner, "NB-IoT technology overview and experience from cloud-RAN implementation," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 26–32, Jun. 2017.

[18] M. Chen, Y. Qian, Y. Hao, Y. Li, and J. Song, "Data-driven computing and caching in 5G networks: Architecture and delay analysis," *IEEE Wireless Commun.*, vol. 25, no. 1, pp. 70–75, Feb. 2018.

[19] 5G Americas. (2017). *LTE Progress Leading to the 5G Massive Internet of Things*. Accessed: Jun. 10, 2020. [Online]. Available:https://www.5gamericas.org/wp-content/uploads/2019/07/LTE_Progress_Leading_to_the_5G_Massive_Internet_of_Things_Final_12.5.pdf

[20] B. Silva, R. M. Fisher, A. Kumar, and G. P. Hancke, "Experimental link quality characterization of wireless sensor networks for underground monitoring," *IEEE Trans. Ind. Informat.*, vol. 11, no. 5, pp. 1099–1110, Oct. 2015.

[21] A. K. Gupta. (2019). *Creating the smart cities of the future A three-tier development model for digital transformation of Citizen Services*. Accessed: Jul. 15, 2020. [Online]. Available: https://www.pwc.com/gx/en/sustainability/assets/creating-the-smart-cities-of-the-future.pdf

[22] S. K. Datta, C. Bonnet, and N. Nikaein, "An IoT gateway centric architecture to provide novel M2M services," in *Proc. IEEE World Forum Internet Things (WF-IoT)*, Mar. 2014, pp. 514–519.

[23] D. C. O. Roos, S. Sauty, and J. Krueger, "Communications for smarter energy systems," ITEL, White Paper 1215/JNW/CAT/XX/PDF, 2019, vol. 1, pp. 1–8. [Online]. Available: https://www.intel.com/content/www/us/en/energy/iot-smarter-energy-systems-paper.html

[24] A. Ghasempour, "Internet of Things in smart grid: Architecture, applications, services, key technologies, and challenges," *Inventions*, vol. 4, no. 1, p. 22, 2019, doi: 10.3390/inventions4010022.

[25] Unicom Mobile, *NB-IoT Commercialisation Case Study, China Mobile-Telecom*, GSMA, London, U.K., 2019, pp. 1–12.

[26] Ericsson, "Cellular networks for massive IoT: Enabling low power wide area applications," Ericsson, Stockholm, Sweden, White Paper, 2016, pp. 1–13.

[27] T. Macaulay, *RIoT Control: Understanding and Managing Risks and the Internet of Things*. San Mateo, CA, USA: Morgan Kaufmann, 2016.

[28] Skyworks. (2020). *Skyworks,Cellular IoT*. Accessed: Apr. 20, 2020. [Online]. Available: www.skyworksinc.com/products/1152/cellularIoT

[29] Mediatek. (2020). *NB-IoT*. Mediatek. 2020 Accessed: Apr. 5, 2020. [Online]. Available:https://www.mediatek.com/news-events/press-releases/mediatek-announces-first-global-lwm2m-over-nidd-nb-iot-commercial-capability

[30] Qualcomm. (2020). *The Qualcomm SnapdragonTM 1200 Wearable Platform Provides Support for LTE Cat-M1 (eMTC) and NB-1 (NB-IoT)*. Qualcomm. Accessed: Apr. 5, 2020. [Online]. Available: https://www.qualcomm.com/products/snapdragon-1200-wearable-platform

[31] SierraWireless. (2020). *Setting a New Standard for IoT Embedded Platforms*. SierraWireless. Accessed: Mar. 22, 2020. [Online]. Available:https://www.sierrawireless.com/products-and-solutions/embedded-solutions/programmable-iot-gateways-modems/

[32] Huawei. (2020). *NarrowBand IoT*. Huawei. Accessed: Mar. 25, 2020. [Online]. Available: https://e.huawei.com/my/solutions/technical/iot/nb-iot

[33] Intel. (2019). *Modem Solutions*. Intel. Accessed: Apr. 28, 2020. [Online]. Available: www.intel.com/content/www/us/en/mobile/modem-solutions.html

[34] T. Mobile. (2019). *Smart Cities*. T. Mobile. Accessed: Apr. 25, 2020. [Online]. Available:http://iot.t-mobile.com/solutions/smart-cities/

[35] U. Blox. (2020). *Cellular Chips and Modules*. Ublox. Accessed: Mar. 25, 2020. [Online]. Available:https://www.u-blox.com/en/cellular-modules

[36] T. Norway. (2020). *Sub-Pump*. Accessed: May 15, 2020. [Online]. Available: www.teliacompany.com/en/news/news-articles/2017/sub-pump/

[37] L. Zhang, G. Zhao, and M. A. Imran, *Internet of Things and Sensors Networks in 5G Wireless Communications*. Basel, Switzerland: MDPI Journal, 2020.

[38] P. Salva-Garcia, J. M. Alcaraz-Calero, Q. Wang, J. B. Bernabe, and A. Skarmeta, ''5G NB-IoT: Efficient network traffic filtering for multitenant IoT cellular networks,'' *Secur. Commun. Netw.*, vol. 2018, pp. 1–21, Dec. 2018, doi: 10.1155/2018/9291506.

[39] Vodafone, *Narrowband-IoT:pushing the boundaries of IoT*, Vodafone, Berkshire, U.K., 2020, pp. 1–16.

[40] R. Ratasuk, J. Tan, N. Mangalvedhe, M. H. Ng, and A. Ghosh, ''Analysis of NB-IoT deployment in LTE guard-band,'' in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5, doi: 10.1109/VTC-Spring.2017.8108184.

[41] A. Ratilainen. *NB-IoT Presentation for IETF LPWAN*. Lpwan@Iet, vol. 97, p. 12. Accessed: Jul. 11, 2020. [Online]. Available: https://datatracker.ietf.org/meeting/97/materials/slides-97-lpwan-30-nb-iot-presentation-00

[42] Thailand. (2019). *Thailand IoT Industry-White Paper*. Thailand. Accessed: May 15, 2020. [Online]. Available: https://www.quectel.com/support/downloads/MarketinResources.htm?keys=ThailandIoTIndustryWhite Paper

[43] J. Xu, J. Yao, L. Wang, Z. Ming, K. Wu, and L. Chen, ''Narrowband Internet of Things: Evolutions, technologies, and open issues,'' *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1449–1462, Jun. 2018, doi: 10.1109/JIOT.2017.2783374.

[44] H. Fattah, *5G LTE Narrowband Internet of Things (NB-IoT)*. Boca Raton, FL, USA: CRC Press, 2019.

[45] S. K. Routray and H. Mohammed Hussein, ''Narrowband IoT: An appropriate solution for developing countries,'' 2019, *arXiv:1903.04850*. [Online]. Available: http://arxiv.org/abs/1903.04850

[46] *Evolved Universal Terrestrial Radio Access, Radio Link Control (RLC) Protocol Specification*, document 3GPP TS 36.322 v11.0.0, Valbonne, France, 2012, vol. 2.

[47] Access, Evolved Universal Terrestrial Radio Access, *Packet Data Convergence Protocol (PDCP) Specification*, Specification, document TS. 36, 2016.

[48] *5G NR: Overall Description; Stage-2 (3GPP TS 38.300 Version 15.3.1 Release 15)*, document TS 138 300-V15.3.1, 2018. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/15.03.01_60/ts_138300v150301p.pdf

[49] G. Aloi, G. Caliciuri, G. Fortino, R. Gravina, P. Pace, W. Russo, and C. Savaglio, ''Enabling IoT interoperability through opportunistic smartphone-based mobile gateways,'' *J. Netw. Comput. Appl.*, vol. 81, pp. 74–84, Mar. 2017.

[50] A. Hoglund, X. Lin, O. Liberg, A. Behravan, E. A. Yavuz, M. Van Der Zee, Y. Sui, T. Tirronen, A. Ratilainen, and D. Eriksson, ''Overview of 3GPP release 14 enhanced NB-IoT,'' *IEEE Netw.*, vol. 31, no. 6, pp. 16–22, Nov. 2017.

[51] R. Ratasuk, N. Mangalvedhe, Z. Xiong, M. Robert, and D. Bhatoolaul, ''Enhancements of narrowband IoT in 3GPP rel-14 and rel-15,'' in *Proc. IEEE Conf. Standards for Commun. Netw. (CSCN)*, Sep. 2017, pp. 60–65.

[52] (2019). *Work Plan Description Releases, 3GPP-A Global Initiative*. Accessed: May 18, 2020. [Online]. Available: htpps://3gpp.org/ftp/Information/WORK_PLAN/Description_Releases/

[53] I. 3GPP Global, *3GPP Archive Specifications*, document Release 15 3GPP TR 21.915 v15.0.0, 2019, Accessed: May 13, 2020. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/21_series/21.915/

[54] 3GPP Global Initiative, *Early Release 16 Status*, document Release 16, 3GPP TR 21.916 v0.4.0, 3GPP-A Global Initiative, 2020, Accessed: May 20, 2020. [Online]. Available: https://www.3gpp.org/release-16.

[55] H. Ruijing. (2019). *Exploring NB-IoT Network to Boost 5G IoT Development*. ZTE Corp. Accessed: Jun. 10, 2020. [Online]. Available: https://www.zte.com.cn/global/about/magazine/zte-technologies/2019/6-en/Expert-Views/2

[56] 3GPP Global Initiative, *3GPP release-17*, document Release 17, 3GPP TR 21.917 Draft Version, 2020. Accessed: May 15, 2020. [Online]. Available: https://www.3gpp.org/release-17

[57] J. Kim, D. Kim, and S. Choi, *3GPP SA2 Architecture and Functions for 5G Mobile Communication System*. Amsterdam, The Netherlands: Elsevier, 2017, pp. 1–8.

[58] P. Marsch, Ö. Bulakci, O. Queseth, and M. Boldi, *5G System Design, Architectural and Functional Considerations and Long Term Research*, 1st ed. London, U.K.: Wiley, 2018.

[59] S. Wang, X. Zhang, Y. Zhang, L. Wang, J. Yang, and W. Wang, ''A survey on mobile edge networks: Convergence of computing, caching and communications,'' *IEEE Access*, vol. 5, pp. 6757–6779, 2017.

[60] I. Parvez, A. Rahmati, I. Guvenc, A. I. Sarwat, and H. Dai, ''A survey on low latency towards 5G: RAN, core network and caching solutions,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 3098–3130, 4th Quart., 2018.

[61] A. Checko, H. L. Christiansen, Y. Yan, L. Scolari, G. Kardaras, M. S. Berger, and L. Dittmann, ''Cloud RAN for mobile networks—A technology overview,'' *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 405–426, 1st Quart., 2015.

[62] G. A. O. Yin, H. A. N. Jiren, L. I. U. Zhuang, L. I. U. Yang, and H. He, ''General architecture of centralized unit and distributed unit for new radio,'' *ZTE Commun.*, vol. 16, no. 2, pp. 23–31, 2018.

[63] GSMA. (2019). *Mobile IoT Network Launches*. Accessed: May 26, 2020. [Online]. Available: https://www.gsma.com/iot/mobile-iot-commercial-launches/

[64] A. Colakovi and M. Hadžialić, ''Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues,'' *Comput. Netw.*, vol. 144, pp. 17–39, Oct. 2018.

[65] E. Hossain and M. Hasan, ''5G cellular: Key enabling technologies and research challenges,'' *IEEE Instrum. Meas. Mag.*, vol. 18, no. 3, pp. 11–21, Jun. 2015.

[66] A. J. Onumanyi, A. M. Abu-Mahfouz, and G. P. Hancke, ''Cognitive radio in low power wide area network for IoT applications: Recent approaches, benefits and challenges,'' *IEEE Trans. Ind. Informat.*, vol. 16, no. 12, pp. 7489–7498, Dec. 2020. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8972333

[67] Y. D. Beyene, ''Algorithms, protocols and cloud-RAN implementation aspects of 5G networks,'' Ph.D. dissertation, Aalto Univ., Helsinki, Finland, 2018.

[68] T. Q. S. Quek, M. Peng, O. Simeone, and W. Yu, *Cloud Radio Access Networks: Principles, Technologies, and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[69] V. Talla, M. Hessar, B. Kellogg, A. Najafi, J. R. Smith, and S. Gollakota, ''Lora backscatter: Enabling the vision of ubiquitous connectivity,'' in *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.*, 2017, vol. 1, no. 3, pp. 1–24.

[70] S.-H. Park, O. Simeone, O. Sahin, and S. Shamai, ''Robust layered transmission and compression for distributed uplink reception in cloud radio access networks,'' *IEEE Trans. Veh. Technol.*, vol. 63, no. 1, pp. 204–216, Jan. 2014.

[71] Y. Shi, J. Zhang, and K. B. Letaief, ''Group sparse beamforming for green cloud-RAN,'' *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2809–2823, May 2014.

[72] D. Darsena, G. Gelli, and F. Verde, "Cloud-aided cognitive ambient backscatter wireless sensor networks," *IEEE Access*, vol. 7, pp. 57399–57414, 2019.

[73] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[74] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: Wireless communication out of thin air," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, 2013.

[75] B. Ji, Z. Chen, S. Chen, B. Zhou, C. Li, and H. Wen, "Joint optimization for ambient backscatter communication system with energy harvesting for IoT," *Mech. Syst. Signal Process.*, vol. 135, Jan. 2020, Art. no. 106412.

[76] X. Lu, G. Li, H. Jiang, D. Niyato, and P. Wang, "Performance analysis of wireless-powered relaying with ambient backscattering," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2018, pp. 1–6.

[77] H. Guo, Q. Zhang, S. Xiao, and Y.-C. Liang, "Exploiting multiple antennas for cognitive ambient backscatter communication," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 765–775, Feb. 2019.

[78] D. Darsena, G. Gelli, and F. Verde, "Modeling and performance analysis of wireless networks with ambient backscatter devices," *IEEE Trans. Commun.*, vol. 65, no. 4, pp. 1797–1814, Apr. 2017.

[79] X. Lin, A. Grovlen, K. Werner, J. Li, R. Baldemair, J.-F.-T. Cheng, S. Parkvall, D. C. Larsson, H. Koorapaty, M. Frenne, and S. Falahati, "5G new radio: Unveiling the essentials of the next generation wireless access technology," *IEEE Commun. Standards Mag.*, vol. 3, no. 3, pp. 30–37, Sep. 2019.

[80] E. Dahlman and S. Parkvall, "NR-the new 5G radio-access technology," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–6.

[81] M. Mozaffari, Y.-P.-E. Wang, O. Liberg, and J. Bergman, "Flexible and efficient deployment of NB-IoT and LTE-MTC in coexistence with 5G new radio," in *Proc. IEEE INFOCOM-IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2019, pp. 391–396, doi: 10.1109/INFCOMW.2019.8845119.

[82] A. A. Zaidi, R. Baldemair, V. Moles-Cases, N. He, K. Werner, and A. Cedergren, "OFDM numerology design for 5G new radio to support IoT, eMBB, and MBSFN," *IEEE Commun. Standards Mag.*, vol. 2, no. 2, pp. 78–83, Jun. 2018.

[83] *NR; Base Station (BS) Radio Transmission and Reception (Release 15)*, 3GPP, document 38.104 V15.3.0, 2018.

[84] L. C. Alexandre, A. L. De Souza Filho, and A. C. Sodre, "Indoor coexistence analysis among 5G new radio, LTE–A and NB-IoT in the 700 MHz band," *IEEE Access*, vol. 8, pp. 135000–135010, 2020.

[85] M. Abbasi and S. Member, "NB-IoT small cell: A 3GPP perspective," 2019, pp. 1–6, *arXiv:1910.00677*. [Online]. Available: https://arxiv.org/abs/1910.00677

[86] C.-W. Huang, S.-C. Tseng, P. Lin, and Y. Kawamoto, "Radio resource scheduling for narrowband Internet of Things systems: A performance study," *IEEE Netw.*, vol. 33, no. 3, pp. 108–115, May 2019, doi: 10.1109/MNET.2018.1700386.

[87] L. Feltrin, G. Tsoukaneri, M. Condoluci, C. Buratti, T. Mahmoodi, M. Dohler, and R. Verdone, "Narrowband IoT: A survey on downlink and uplink perspectives," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 78–86, Feb. 2019, doi: 10.1109/MWC.2019.1800020.

[88] H. Li, G. Chen, Y. Wang, Y. Gao, and W. Dong, "Accurate performance modeling of uplink transmission in NB-IoT," in *Proc. IEEE 24th Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2018, pp. 910–917.

[89] J. Zou and C. Xu, "Frequency offset tolerant synchronization signal design in NB-IoT," *Sensors*, vol. 18, no. 11, p. 4077, Nov. 2018.

[90] A. Shimura, M. Sawahashi, S. Nagata, and Y. Kishiyama, "Physical cell ID detection performance applying frequency diversity reception to NPSS and NSSS for NB-IoT," in *Proc. 24th Asia–Pacific Conf. Commun. (APCC)*, Nov. 2018, pp. 514–519.

[91] M. Agiwal, M. K. Maheshwari, and H. Jin, "Power efficient random access for massive NB-IoT connectivity," *Sensors*, vol. 19, no. 22, p. 4944, Nov. 2019.

[92] J.-K. Hwang, C.-F. Li, and C. Ma, "Efficient detection and synchronization of superimposed NB-IoT NPRACH preambles," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 1173–1182, Feb. 2019.

[93] R. Harwahyu, R.-G. Cheng, W.-J. Tsai, J.-K. Hwang, and G. Bianchi, "Repetitions versus retransmissions: Tradeoff in configuring NB-IoT random access channels," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3796–3805, Apr. 2019.

[94] R. Harwahyu, R.-G. Cheng, C.-H. Wei, and R. F. Sari, "Optimization of random access channel in NB-IoT," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 391–402, Feb. 2018.

[95] S. Martiradonna, G. Piro, and G. Boggia, "On the evaluation of the NB-IoT random access procedure in monitoring infrastructures," *Sensors*, vol. 19, no. 14, p. 3237, Jul. 2019.

[96] E. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*. New York, NY, USA: Academic, 2018.

[97] V. Savaux, "DFT-based low-complexity optimal cell ID estimation in NB-IoT," *EURASIP J. Adv. Signal Process.*, vol. 2020, no. 1, pp. 1–12, Dec. 2020.

[98] M. K. Hossain Jewel, R. Sale Zakariyya, O. J. Famoriji, M. S. Ali, and F. Lin, "A low complexity channel estimation technique for NB-IoT downlink system," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2019, pp. 1–3.

[99] M. S. Ali, Y. Li, M. K. H. Jewel, O. J. Famoriji, and F. Lin, "Channel estimation and Peak-to-Average power ratio analysis of narrowband Internet of Things uplink systems," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–15, Jul. 2018.

[100] A. Farzamnia, N. W. Hlaing, M. K. Haldar, and J. Rahebi, "Channel estimation for sparse channel OFDM systems using least square and minimum mean square error techniques," in *Proc. Int. Conf. Eng. Technol. (ICET)*, Aug. 2017, pp. 1–5.

[101] M. R. Bai, P.-J. Hsieh, and K.-N. Hur, "Optimal design of minimum mean-square error noise reduction algorithms using the simulated annealing technique," *J. Acoust. Soc. Amer.*, vol. 125, no. 2, pp. 934–943, Feb. 2009.

[102] 3GPPspecs Tech-Invite, *E-UTRA–Narrowband Internet of Things–Technical Report for BS and UE Radio Transmission and Reception*, 3GPP, document TR 36.802 RAN4, 2016. [Online]. Available: https://www.tech-invite.com/3m36/tinv-3gpp-36-802.html

[103] S. Liu, L. Xiao, Z. Han, and Y. Tang, "Eliminating NB-IoT interference to LTE system: A sparse machine learning-based approach," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 6919–6932, Aug. 2019.

[104] H. Zhao, M. Li, R. Wang, Y. Liu, and D. Song, "Compressed sensing theory-based channel estimation for optical orthogonal frequency division multiplexing communication system," *Opt. Commun.*, vol. 326, pp. 94–99, Sep. 2014.

[105] S. Liu, F. Yang, J. Song, and Z. Han, "Block sparse Bayesian learning-based NB-IoT interference elimination in LTE-advanced systems," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4559–4571, Oct. 2017.

[106] E. Pateromichelakis, M. Shariat, A. ul Quddus, and R. Tafazolli, "On the evolution of multi-cell scheduling in 3GPP LTE/LTE-A," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 701–717, 2nd Quart., 2013.

[107] E. Hossain, M. Rasti, H. Tabassum, and A. Abdelnasser, "Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 118–127, Jun. 2014.

[108] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 10–21, Jun. 2011.

[109] ETSI Technical Specification, *Technical Specification Group Radio Access Network Evolved Universal Terrestrial Radio Access (E-UTRA)*, 3GPP, document TS 36.300, 2015. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/136300_136399/136300/09.04.00_60/ts_136300v090400p.pdf

[110] *Coordinated Multi-Point Operation for LTE Physical Layer Aspects; (Release 11)'v11.2.0.*, 3GPP, document TR 36.819, 2013.

[111] B. Soret, P. Mogensen, K. I. Pedersen, and M. C. Aguayo-Torres, "Fundamental tradeoffs among reliability, latency and throughput in cellular networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 1391–1396.

[112] K. I. Pedersen, G. Berardinelli, F. Frederiksen, P. Mogensen, and A. Szufarska, "A flexible 5G frame structure design for frequency-division duplex cases," *IEEE Commun. Mag.*, vol. 54, no. 3, pp. 53–59, Mar. 2016.

[113] H. Malik, H. Pervaiz, M. Mahtab Alam, Y. Le Moullec, A. Kuusik, and M. Ali Imran, "Radio resource management scheme in NB-IoT systems," *IEEE Access*, vol. 6, pp. 15051–15064, 2018.

[114] H. Malik, M. M. Alam, H. Pervaiz, Y. L. Moullec, A. Al-Dulaimi, S. Parand, and L. Reggiani, "Radio resource management in NB-IoT systems: Empowered by interference prediction and flexible duplexing," *IEEE Netw.*, vol. 34, no. 1, pp. 144–151, Jan. 2020.

[115] Y. Nam, J. So, M. Na, and C. Choi, "Coverage class adaptation schemes considering device characteristics in a 3GPP narrowband IoT system," *J. Korean Inst. Commun. Inf. Sci.*, vol. 41, no. 9, pp. 1026–1037, Sep. 2016.

[116] S. Cluzel, L. Franck, J. Radzik, S. Cazalens, M. Dervin, C. Baudoin, and D. Dragomirescu, "3GPP NB-IOT coverage extension using LEO satellites," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–5.

[117] S. Ravi, P. Zand, M. El Soussi, and M. Nabi, "Evaluation, modeling and optimization of coverage enhancement methods of NB-IoT," in *Proc. IEEE 30th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2019, pp. 1–7.

[118] K. I. Pedersen, M. Niparko, J. Steiner, J. Oszmianski, L. Mudolo, and S. R. Khosravirad, "System level analysis of dynamic user-centric scheduling for a flexible 5G design," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[119] Q.-S. Hu, X.-N. Fan, and Z.-Y. Li, "A simple and efficient link adaptation method for narrowband Internet of Things," in *Proc. IEEE 21st Int. Conf. High Perform. Comput. Commun.; IEEE 17th Int. Conf. Smart City; IEEE 5th Int. Conf. Data Sci. Syst. (HPCC/SmartCity/DSS)*, Aug. 2019, pp. 2606–2609.

[120] C. Yu, L. Yu, Y. Wu, Y. He, and Q. Lu, "Uplink scheduling and link adaptation for narrowband Internet of Things systems," *IEEE Access*, vol. 5, pp. 1724–1734, 2017.

[121] GSMA. (2019). *NB-IoT Deployment guide to Basic Feature Set Requirements*. [Online]. Available: https://www.gsma.com/iot/resources/nbiot-deployment-guide-v3/

[122] Y. Guo and M. Xiang, "Multi-agent reinforcement learning based energy efficiency optimization in NB-IoT networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2019, pp. 1–6.

[123] Y. Gu and W. Feng, "Research on stochastic resonance enhanced coverage and power control in NB-IoT," in *Proc. IEEE 19th Int. Conf. Commun. Technol. (ICCT)*, Oct. 2019, pp. 317–322.

[124] D. Di Lecce, A. Grassi, G. Piro, and G. Boggia, "Boosting energy efficiency of NB-IoT cellular networks through cooperative relaying," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1–5.

[125] 3GPP Global Initiative, *Evolved Universal Terrestrial Radio Access (E-UTRA) Medium Access Control (MAC) protocol Specification*, 3GPP, document TS 36.321, 2017.

[126] Y. Miao, W. Li, D. Tian, M. S. Hossain, and M. F. Alhamid, "Narrowband Internet of Things: Simulation and modeling," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2304–2314, Aug. 2018.

[127] Y. D. Beyene, R. Jantti, K. Ruttik, and S. Iraji, "On the performance of narrow-band Internet of Things (NB-IoT)," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6.

[128] M. Rupp, S. Schwarz, and M. Taranetz, *The Vienna LTE-Advanced Simulators*. Singapore: Springer, 2016, doi: 10.1007/978-981-10-0617-3.

[129] P. Jorke, R. Falkenberg, and C. Wietfeld, "Power consumption analysis of NB-IoT and eMTC in challenging smart city environments," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–6.

[130] Y. Sun, F. Tong, Z. Zhang, and S. He, "Throughput modeling and analysis of random access in narrowband Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1485–1493, Jun. 2018.

[131] G. Fortino, R. Gravina, W. Russo, and C. Savaglio, "Modeling and simulating Internet-of-Things systems: A hybrid agent-oriented approach," *Comput. Sci. Eng.*, vol. 19, no. 5, pp. 68–76, 2017.

[132] A. Virdis, G. Stea, and G. Nardini, "Simulating LTE/LTE-advanced networks with simuLTE," in *Simulation and Modeling Methodologies, Technologies and Applications*. Cham, Switzerland: Springer, 2015, pp. 83–105.

[133] S. Luke, C. Cioffi-Revilla, L. Panait, K. Sullivan, and G. Balan, "MASON: A multiagent simulation environment," *Simulation*, vol. 81, no. 7, pp. 517–527, Jul. 2005.

[134] P. A. Lopez, E. Wiessner, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flotterod, R. Hilbrich, L. Lucken, J. Rummel, and P. Wagner, "Microscopic traffic simulation using SUMO," in *Proc. 21st Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 2575–2582.

[135] L. Fuhong, L. Qian, Z. Xianwei, C. Yueyun, and H. Daochao, "Cooperative differential game for model energy-bandwidth efficiency tradeoff in the Internet of Things," *China Commun.*, vol. 11, no. 1, pp. 92–102, Jan. 2014.

[136] G. Kecskemeti, G. Casale, D. N. Jha, J. Lyon, and R. Ranjan, "Modelling and simulation challenges in Internet of Things," *IEEE Cloud Comput.*, vol. 4, no. 1, pp. 62–69, Jan./Feb. 2017.

[137] T. Goyal, A. Singh, and A. Agrawal, "Cloudsim: Simulator for cloud computing infrastructure and modeling," *Procedia Eng.*, vol. 38, pp. 3566–3572, 2012.

[138] G. Research. (2019). *Narrowband-IoT Market Size, Share & Trends Analysis Report By Component (Network, Module), By Deployment (In-band, Guard-band, Standalone), By Device Type, By End Use, By Region, And Segment Forecasts, 2019–2025*. Grandview Res. Accessed: May 29, 2020. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/narrowband-nb-iot-market

[139] *NB-IoT-Enabling New Business Opportunities*, Huawei, Shenzhen, China, 2015, pp. 1–22, vol. 2.

[140] Market and Market. (2016). *Narrowband IoT Market by Application Software, Technology Service, Vertical, Smart Application (Smart Governance, Smart Metering, Smart Homes, Smart Asset Tracking), and Region- Global Forecast to 2022*. Market Market. Accessed: Jun. 17, 2020. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/narrowband-iot-enterprise-application-market-195605629.html

[141] S. R. Khosravirad, K. I. Pedersen, L. Mudolo, and K. Bakowski, "HARQ enriched feedback design for 5G technology," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–4, doi: 10.1109/VTC-Fall.2016.7881032.

[142] A. S. Gbadamosi, "Cloud-based IoT monitoring system for poultry farming in nigeria," *Arid Zo. J. Eng. Technol. Environ.*, vol. 16, pp. 100–108, Mar. 2020.

[143] GSMA. (2018). *Agriculture Using NB-IoT*. [Online]. Available: https://www.gsma.com/iot/wp-content/uploads/2018/10/201810_GSMA_IoT-Development_Guide_NB-IoT_for_Agriculture.pdf

[144] J. Guerrero-Ibáñez, S. Zeadally, and J. Contreras-Castillo, "Sensor technologies for intelligent transportation systems," *Sensors*, vol. 18, no. 4, p. 1212, Apr. 2018.

[145] A. S. Gbadamosi and N. U. Galadima, "Promoting an IoT-based waste-bin management system in higher institution," *J. Sci. Technol. Math. Educ.*, vol. 15, no. 4, pp. 48–55, 2019. [Online]. Available: https://jostmed.futminna.edu.ng/images/JOSTMED/JOSTMED_15_4_DECEMBER_2019/5._Promoting_An_IoT-Based_waste-bin_management_system_in_Higher_Institution.pdf

[146] M. B. Hassan, E. S. Ali, R. A. Mokhtar, R. A. Saeed, and B. S. Chaudhari, "NB-IoT: Concepts, applications, and deployment challenges," in *LPWAN Technologies for IoT and M2M Applications*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 119–144.

[147] H. Zhang, J. Li, B. Wen, Y. Xun, and J. Liu, "Connecting intelligent things in smart hospitals using NB-IoT," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1550–1560, Jun. 2018.

[148] *Study on new radio access technology physical layer aspects', V14.1.0*, 3GPP, document TR.38.802, 2017. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/38_series/38.802/

[149] H. 2020. (2017). *Flexible Air iNTerfAce for Scalable service delivery wiThin wIreless Communication networks of the 5th Generation (FANTASTIC-5G)*. [Online]. Available: http://fantastic5g.com/wp-content/uploads/2017/05/FANTASTIC-5G_D42_final.pdf

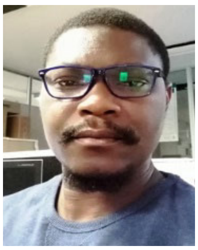
[150] K. Chatzikokolakis, "On the way to massive access in 5G: Challenges and solutions for massive machine communications," in *Proc. Int. Conf. Cogn. Radio Oriented Wireless Netw.*, 2015, pp. 708–717.

[151] H. 2020. (2016). *Flexible Air Interface for Scalable service delivery within wIreless Communication networks of the 5th Generation (FANTASTIC-5G)*. [Online]. Available: https://docplayer.net/52709932-Public-deliverable-d4-1-technical-results-for-service-specific-multi-node-multi-antenna-solutions.html

[152] Cambridge Inovation Institute. (2020). *Vodafone Starts on NB-IoT Interoperability Testing With Vendors*. Ointernet Bus. Accessed: Jun. 10, 2020. [Online]. Available: https://internetofbusiness.com/vodafone-nb-iot-interoperability/

[153] J. Cao, P. Yu, M. Ma, and W. Gao, "Fast authentication and data transfer scheme for massive NB-IoT devices in 3GPP 5G network," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1561–1575, Apr. 2019.

[154] M. Rumney, P. Kyösti, and L. Hentilä, "3GPP channel model developments for 5G NR requirements and testing," in *Proc. 12th Eur. Conf. Antennas Propag.*, 2018, pp. 1–5.



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