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Understanding the Potentials of Narrowband Internet of Things (NB-IoT) Cellular Technology: Salient Features, Architecture, Smart Applications and Quality of Service (QoS) Challenges

MUHAMMAD WASEEM [1], ALICIA LOPEZ [1,2], PEDRO LUIS CARRO [1,3] (Fellow, IEEE), MARIA ANGELES LOSADA [1,2], DWIGHT RICHARDS [4] (Member, IEEE), AND ABDUL AZIZ [5] (Member, IEEE)

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[1]Department of Electronic Engineering and Communications, Universidad de Zaragoza, 50018 Zaragoza, Spain
[2]GTF, Aragón Institute of Engineering Research, Universidad de Zaragoza, 50018 Zaragoza, Spain
[3]CeNIT, Aragón Institute of Engineering Research, Universidad de Zaragoza, 50018 Zaragoza, Spain
[4]College of Staten Island-CUNY, City University of New York, New York, NY 10314 USA
[4]Department of Computer Science and Systems Engineering, Universidad de Zaragoza, 50018 Zaragoza, Spain

CORRESPONDING AUTHOR: M. WASEEM (e-mail: mwaseem@unizar.es)

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ABSTRACT Since the last decade, the number of Internet of Things (IoT) devices has increased dramatically and to operate them at low power has been a great challenge. Therefore, significant efforts have been made by the researchers to innovate such technologies that may operate the IoT devices at low power. In this context, several Low Power Wide Area Network (LPWAN) technologies have been introduced which have revolutionized the world of IoT. Narrowband Internet of Things (NB-IoT) is one of the protocols that was developed by 3rd Generation Partnership Project (3GPP) in June 2016 to cater the stringent requirements of IoT devices. In this paper, a comprehensive analysis on the features, architecture, signals and channels of NB-IoT is provided. Additionally, a detailed description of the applications of NB-IoT is also presented. Finally, some crucial challenges related to the quality of service (QoS) of NB-IoT are highlighted in this paper.

INDEX TERMS NB-IoT, NB-IoT features, NB-IoT architecture, modes of NB-IoT, NB-IoT frame structure, signals and channels of NB-IoT, NB-IoT smart applications, QoS challenges.

I. INTRODUCTION

THE INTERNET of Things (IoT) is a ubiquitous network technology [1], in which a huge number of objects, belonging to different environments, interact and communicate with each other for collecting, processing and exchanging data through different Internet protocols and interfaces. This technology can not only provide a communication between the physical objects, such as different sensors and actuators in industry, vehicles, homes and cities, but also supports software applications over a large scale. The field of telecommunication has been revolutionized by this communications paradigm because it has appeared as a bridge amongst the diverse technologies and has enabled new applications and provided connectivity amongst billions of objects. In IoT, a huge amount of information is generated and exchanged, allowing for remote decision-making and control. The growth in this technology is quite dramatic and its worldwide social and economic impact is expected to be highly significant. Many business sectors, such as manufacturing, agriculture, health, transportation and logistics will be improved and will grow rapidly through the forthcoming developments in this technology. There is prediction of $11.1 trillion per year in the total impact of cross sector including IoT applications consumer surplus by 2025 [2]. In addition, it is speculated that in the near future, the total number of devices connected through IoT will reach 18 billion and every person will have 1.8 connections worldwide. Hence, in the last years, in order to meet the stringent requirements of the industry, significant technological efforts have been made to address the expected market growth of IoT technology regarding connected devices, applications and investments. In fact, recently Machine Type Communications (MTC) have gained a momentous importance as they can deliver a wide range of services and applications for both industries and individuals by providing connectivity via wireless systems. In order to support the applications of MTC, several protocols and standards have been developed, such as ZigBee, WiFi, RFID, NFC, Low-energy Bluetooth or Z-Wave. Most of these protocols and standards were developed for short-range applications and are not suitable for long-range communication networks. Therefore, in order to provide communications between the objects for long-range applications, new Low Power Wide Area Network (LPWAN) technologies were simultaneously devised, such as Sigfox, RPMA, Weightless SIG, LoRa, and LoRaWAN. Although these technologies can be used to achieve massive connectivity, new infrastructure deployments are mandatory for them to operate in the unlicensed spectrum.

Narrowband Internet of Things (NB-IoT) emerged as a promising solution to deal with MTC connectivity and was introduced in June 2016 by the 3rd Generation Partnership Project (3GPP) to improve low power connectivity of IoT devices and to offer IoT services by using wide area cellular networks. This technology was developed to support low power and low complexity devices [3] that will serve in those areas where radio coverage was assumed to be very poor [4]. The coverage and capacity improvements can be attained through the narrowband transmission [5]. NB-IoT has been designed by using the existing characteristics of the legacy Long Term Evolution (LTE) maintaining co-existence of both technologies [6] and, therefore, it is operated in the licensed spectrum. NB-IoT takes into account the requirements of IoT devices and services, in which low power consumption, low cost connectivity, good indoor coverage, support of massive connections and network architecture optimization are crucial. In addition, the installation of an IoT network in NB-IoT does not require a new infrastructure, since the existing LTE infrastructure can be reused, thus allowing for reduced complexity and cost.

This paper presents a systematic review on NB-IoT technology, in comparison with other LPWAN technologies, such as Sigfox and LoRa, NB-IoT architecture, NB-IoT operation modes, frame structures of uplink and downlink, signals and channels used in NB-IoT, its industrial applications along with a brief description of QoS related challenges in the industrial domains.

A. RELATED WORK

Nowadays, NB-IoT technology has gained a considerable interest from both academia and industry. In this context, several review, survey and technical papers have been published about NB-IoT, and some of them have been summarized in Table 1. In this regard, most of the papers (i.e., [7], [8], [9], [10], [11], [12], [13], [14], [15]) describe the background and design objectives, such as low power consumption, low cost, huge connectivity and improved coverage. Similarly, various articles, such as [16], [17], [18] and [19], provide a comparison of low power wide area network (LPWAN) technologies. Likewise, there are several articles e.g., [10], [11], [18], [20], [21], [22], [23], [24], [25], [26], [27], [28], which discuss the applications of NB-IoT in the industrial environment. Moreover, there are a few papers,[11], [29], [30] which present the architecture and operation modes of NB-IoT. Furthermore, a few papers [9], [14], outline the QoS challenges found in NB-IoT. Besides the aforementioned articles, [12] and [31] analyze the signals and challenges of NB-IoT.

B. RESEARCH GAP

Although the number of studies on NB-IoT is growing rapidly, there are still several critical gaps found in the existing literature. For example, there are various papers which outline the objectives and features of NB-IoT, however, only few articles provide an in-depth knowledge about the operational modes and architecture of NB-IoT, and the frame structures in an integrated manner. In addition, studies based on comparative analyses of NB-IoT with other LPWAN technologies, e.g., LoRa and Sigfox are mostly deficient in scope, which make it difficult for researchers and professionals to make deployment strategic decisions. Moreover, in the current literature, one of the insufficiently addressed areas is the comprehensive taxonomy and parameterization of NB-IoT signals and channels. In most of the existing literature on NB-IoT, these elements are treated at a high level and the granular technical specifications and performance implications of individual signal and channel parameters are excluded. Consequently, an insufficient technical clarity, especially for system level design and optimization, is observed. Additionally, despite the increasing adoption of NB-IoT in the industrial applications, comprehensive evaluations supported by real world case studies and simulations, focusing on Quality of Service (QoS) challenges in these domains are rare. Furthermore, industrial environments have dynamic nature, that introduces specific latency, coverage, and reliability requirements, which are inadequately addressed in the existing literature.

C. PAPER CONTRIBUTIONS

The aim of this paper is to bridge the aforementioned gaps by offering the following key contributions:

- Comprehensive Review on the Fundamentals of NB-IoT: We present an organized and detailed review on the design objectives and salient features of NB-IoT to provide a foundational understanding of NB-IoT for the researchers and practitioners.

TABLE 1. Highlights of the related work.

Ref	Year	Key Contributions
[32]	2024	Surveys on NB-IoT random access, comparison of NB-IoT with other LPWAN technologies, design challenges and requirements of random access in NB-IoT.
[19]	2024	Presents a comparison of NB-IoT and LoRaWAN in terms of latency, power consumption, security and throughput perspectives and proposes sustainable prospects that licensed and unlicensed LPWANs could provide with regard to IoT evolution in developing countries.
[33]	2024	Describes a comprehensive assessment of the performance metrics of NB-IoT and LoRaWAN.
[17]	2024	Provides a comparison of NB-IoT, Sigfox and LoRa for IoT LPWAN Technologies in the Agribusiness.
[18]	2023	Proposes a coverage analysis of NB-IoT and LoRa technologies on LPWAN based agricultural vehicle tracking application.
[27]	2022	Discusses a detailed analysis on NB-IoT and LoRaWAN technologies, considering industrial aspects, both at physical and link layers, and regulatory challenges.
[30]	2022	Provides the features and architecture of the NB-IoT Network.
[16]	2021	Presents a comparison of the emerging LPWAN technologies such as LoRa, Sigfox and NB-IoT.
[9]	2021	Discusses the cellular wireless network standards of NB-IoT, which addresses many key requirements of the IoT and explains to industrial users how to utilize NB-IoT features for their own IoT projects.
[34]	2020	Provides a literature review on resource allocation for NB-IoT.
[35]	2020	Discusses objectives, resource management performance and challenges of NB-IoT.
[11]	2018	Surveys on energy efficient NB-IoT: architecture, applications and challenges.
[12]	2018	Highlights the different challenges related to the Quality of Services (QoS) of NB-IoT.
[36]	2017	Surveys on LPWAN technologies such as LoRa and NB-IoT. Also proposes architecture of NB-IoT network.
[29]	2017	Describes the 3GPP NB-IoT system architecture.
[37]	2017	Explains the different downlink and uplink signals and channels used in NB-IoT.
[8]	2016	Presents a review on NB-IoT, including its several features, design objectives, signals and channels.

- Comparative Evaluation with Competing LPWAN Technologies: We present a structured comparison of NB-IoT with other LPWAN technologies, such as LoRa and Sigfox, on the basis of performance metrics, e.g., power consumption, latency and coverage etc., to understand their operational and technical differences and to choose the most viable solution on the basis of application requirements.
- Detailed Analysis of Operating Modes and Architecture of NB-IoT: We provide an extensive explanation of the operational modes along with the architecture of NB-IoT, while enhancing the reader's comprehension of system-level operations.
- Novel Taxonomy of NB-IoT Signals and Channels: A unique aspect of our work is the development of a detailed taxonomy, covering all downlink and uplink signals and channels used in NB-IoT. In this context, we delve into their significant roles, configurations and parameters to fill to a major technical gap in the existing literature.
- Exploration of Real World Applications: We bring into light the significance and usability of NB-IoT in real world applications by mapping its features into a plenty of use cases.
- In-depth Analysis of QoS Related Challenge through Case Studies and Simulations: We conduct a detailed analysis of NB-IoT QoS related challenges, specifically in the industrial environments.

In this paper, we have reviewed the research carried out in recent years, particularly in the field of NB-IoT applications, considering the significant contributions. The review process involves a detailed analysis of the important contributions made by different conference papers, journal articles, books and thesis reports etc. In this context, we have followed a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach in the research methodology. We have logically queried the scholarly databases to extract useful information from the identified literature. In this regard, we pulled a total of 300 papers out of the databases, amongst them 102 were selected and thoroughly studied, analyzed and classified on the basis of their review areas. In the first process, we performed a quick screening to exclude the papers on the basis of full text unavailability, duplication, written in non-English languages and wrongfully text categorization regarding the interest of area of review. We started the review process by including the papers on the basis of their titles, abstracts, keywords and conclusions. Finally, a total of 102 papers were selected on the basis of the article type, such as review or survey, theoretical or practical etc. At this stage, we also extracted the data to include both theoretical and experimental contents. At the third stage of the review process, we focused on the Quality of Service (QoS) challenges of NB-IoT technology. By highlighting these aspects thoroughly, this paper not only synthesizes the existing literature but also contributes original technical insights about NB-IoT, which are rare in the existing NB-IoT literature.

D. PAPER ORGANIZATION

After the introduction section, the paper is organized as follows: In Section II, a detailed description of NB-IoT in

TABLE 2. Comparison of NB-IoT with Sigfox and LoRa.

Parameters	Sigfox	LoRa	NB-IoT
Origin [16]	France	France	USA
Standardization [43]	Sigfox	LoRa Alliance	3GPP
Transmit Power [44]	20 dBm	Up to 27 dBm	23 dBm
Bandwidth [41]	100 Hz	$<$ 500 kHz	180 kHz & 200 kHz (only in Standalone operation mode)
Modulation Technique [42]	BPSK	Chirp Spreading Spectrum (CSS)	QPSK
Coverage [40]	165 dB	165 dB	164 dB
Spectrum [45]	Unlicensed	Unlicensed	Licensed LTE
Spectrum Cost [46]	Free	Free	$>$ €500 million per MHz
Range	63 km [47]	22 km	Urban: 1.5 km, Rural: 20-40 km [48]
Battery Life [20]	10-15 years	10-15 years [38]	$>$10 years
Energy efficiency	Very small amount of energy is consumed	Very high	Medium High
Mobility [44]	No	Yes	Yes [49]
Maximum messages per day [50]	140 (Uplink) & 4 (Downlink)	Unlimited	Unlimited
Cell Capacity [40]	1,000,000	40,000	200,000
Latency [44]	Medium	Medium	Low
Data Rates [47]	100 bps	50 kbps	250 kbps
Immunity against Interference [42]	Very High	Very High	Low
Mode of communication [44]	Asynchronous Communication	Asynchronous Communication	Synchronous Communication
Duplex communication [42]	Limited Half Duplex	Half Duplex	Half Duplex
Payload Size [40]	12 bytes (Uplink), 8 bytes (Downlink)	243 bytes	1600 bytes
Localization [42]	Yes	Yes	Yes [44]

comparison with other LPWAN technologies, is provided. Moreover, the core design objectives and salient features of NB-IoT are discussed in Section III. NB-IoT architecture is explained in Section IV. Additionally, a detailed analysis of the deployment options, i.e., operational modes of NB-IoT, is presented in Section V. Besides this, a brief description of the frame structures of downlink and uplink of NB-IoT, is provided in Section VI. In addition, Section VII presents a comprehensive exposition of the signals and channels of NB-IoT. Moreover, Section VIII discusses the smart applications of NB-IoT. Over and above, some crucial challenges related to the quality of service (QoS) of NB-IoT are highlighted in Section IX. Finally, conclusions are drawn in Section X.

II. COMPARISON OF NB-IOT WITH SIGFOX AND LORA

As the current wireless networks such as Wi-Fi, Bluetooth, and ZigBee have high data rates and limited coverage offerings, due to which, they are not considered the viable solutions for IoT applications. In this situation, LPWAN technologies can be significantly useful for the IoT applications due to their low data rates and low-cost traits [38]. Nowadays, LPWAN technologies have gained a significant position in the market. The proliferation in the LPWAN based connections is escalating at a rapid pace. It is expected that the growth in LPWAN technologies will reach up to 81% by 2025 with 48% corresponding to NB-IoT [39]. In order to choose an appropriate LPWAN technology for the different IoT applications, it is indispensable to deeply analyze several specifications such as coverage, cell capacity, range in urban and rural areas, battery life, latency, data rates, bandwidth, modulation techniques used, immunity against interference, mode of communication, payload size, localization, mobility, quality of service (QoS) and computational cost [40], [41]. Table 2 presents a comparison [42] of NB-IoT with other proprietary LPWAN technologies: Sigfox and LoRa, to analyze the major differences among them.

Both Sigfox and LoRa are deployed in the unlicensed bands in contrast to NB-IoT which belongs to licensed cellular IoT technologies [50]. Thus, Sigfox and LoRa suffer from fading and multipath, resulting in a lower level of quality of service (QoS). In fact, the unlicensed bands are shared by the different technologies due to which the collisions and interference are increased. On the other hand, the licensed bands have controlled interference because they are allocated only to the operators. Moreover, stringent power limitations are imposed on unlicensed bands by the regulatory bodies. Nonetheless, the allowed transmit power in the licensed bands is quite higher, e.g., 23 dBm in case of NB-IoT. In addition, NB-IoT uses HARQ, QPSK and OFDMA to deal with fading and multipath. In contrast, LoRa and Sigfox use CSS and Ultra Narrowband (UNB) respectively, which are not considered significantly useful against the problems of fading and multipath. Therefore, a better quality of service (QoS) is offered by NB-IoT which is an ideal choice for all those applications, where the requirement of high QoS is imperative [40]. NB-IoT has a range of 1.5 km in urban areas and of 20-40 km in rural areas [47], and also requires access to LTE coverage [40]. Therefore, it is not the best choice for the longest range. On the other hand, Sigfox is considered the best option for providing enhanced range (63 km approximately) [46]. Nevertheless, the coverage level of all the three LPWAN technologies (Sigfox, LoRa and NB-IoT) is very similar, with Sigfox and LoRa 1 dB above the coverage level of NB-IoT, which is 164 dB. Regarding cell capacity, Sigfox has the highest level with nearly one million users per cell, followed by NB-IoT with a fifth of that value. Latency in NB-IoT is comparatively lower than in both Sigfox and LoRa, and thus, it is the most suitable option for IoT applications that require reduced latency. Furthermore, the maximum allowed payload size in NB-IoT is 1600 bytes. By contrast, the allowed payload size in LoRa is 243 bytes, while Sigfox has the least allowed payload size, which is only 12 bytes. This small payload size limits the utilization of Sigfox on several applications of IoT, that require to send large data sizes [38]. Moreover, NB-IoT provides the highest data rates (250 kbps) over Sigfox and LoRa, which have data rates of 50 kbps and 0.1 kbps, respectively.

Regarding energy consumption, end devices in NB-IoT, LoRa and Sigfox, enter into the sleep mode while they are out of operation, which results in a reduction of energy consumption so that lifetime of the end devices is prolonged. Nonetheless, in NB-IoT, the end devices consume extra energy due to synchronous communication and handling of quality of services (QoS). In addition, more peak current is also required in NB-IoT due to its support for OFDM/FDMA formats that further reduces battery lifetime of the NB-IoT end devices as compared to LoRa and Sigfox. Even so, NB-IoT has a battery life of more than 10 years. From the economical point of view, NB-IoT is not considered a very cost effective solution if different factors such as licensed spectrum, network deployment and device cost are involved in the calculation of total cost. However, these costs are shared with other services provided by LTE networks.

In summary, NB-IoT is the most reliable cellular communication LPWAN technology that can provide the best QoS at the highest data rates with the minimum latency and the highest value of payload lengths compared to Sigfox and LoRa. NB-IoT can also provide a long battery life [51] along-with improved indoor coverage, deep penetration, propagation and deployment flexibility with the other networks such as LTE or 5G and beyond. These features are derived from the fact that NB-IoT is designed by using the functionalities of the existing LTE technology [7].

III. NB-IOT: DESIGN OBJECTIVES AND SALIENT FEATURES

NB-IoT has many advantages over other LPWAN technologies as most of the features of LTE have been reused in NB-IoT, such as channels and signals with some necessary simplifications and optimizations to improve the low power connectivity of IoT devices. Table 3 provides a summary of most of the salient features of NB-IoT.

In this context, a description of the key objectives and features of NB-IoT, such as Deep Coverage, Support for Massive connectivity, Low Power Consumption, Reduced Complexity, Spectrum Refarming, Security and Reliability [53], is presented in the following subsections.

A. DEEP COVERAGE

NB-IoT is a technology that can resolve the coverage problem for the indoor and outdoor networks simultaneously [54]. It can provide an extended coverage, which is 20 dB [35] more than the legacy LTE network. The maximum coupling loss (MCL) supported by the conventional LTE is 144 dB, while the MCL supported by NB-IoT is 164 dB [8]. MCL is a parameter, by which the coverage level of a system can be defined, i.e., whether a particular coverage level is supported by the system or not. It can be measured by the following equation (1) [21], which is given by:

$$MCL = P_{TX} - \left(10\log_{10}(BW) + N_0 + SINR + NF\right) \quad (1)$$

where P_{TX} represents the maximum transmitted power, N_F shows the noise figure of the receiver, BW denotes the signal bandwidth, $SINR$ is the signal to interference and noise ratio, whereas the thermal noise one-sided power spectral density (−174 dBm/Hz) is represented by N_0. By reducing the bandwidth and increasing the number of repetitions of the data transmission, an increased coverage can be achieved as per the 3GPP Standards. In fact, bandwidth reduction of NB-IoT is quite useful because the same transmission power is maintained by LTE-eNodeB as is sustained by LTE, which is 43 dBm. As a result, the power spectral density (PSD) level is higher. Similarly, the bandwidth of NB-IoT can be decreased up to 3.75 kHz in case of uplink, whereas 200 kHz bandwidth is carried by GPRS. Thus, the obtained ratio of power spectral density is 5.3, which is nearly equal to 7 dB [9]. So, the first contribution in achieving the goal of coverage enhancement can be attained by decreasing the bandwidth of NB-IoT. Secondly, data packets retransmission is also helpful in achieving this goal of coverage enhancement, which depends upon the individual radio conditions because an IoT message will be retransmitted many times in the difficult areas by an NB-IoT device so that the chance of correct decoding of the received message by the eNodeB, may be increased. In this context, Fig. 1 shows the three levels of coverage enhancement, which have been denoted by CE0, CE1 and CE2 respectively [3], [9]. The standard coverage level of LTE has been represented as CE0 and the level where the coverage is expected to be very poor, is specified as CE2. However, different CE levels can be defined depending upon the network. These coverage enhancement levels play their role in the repetition of the messages many times. In level CE0, data is not repeated by the device because it is under the standard coverage of LTE. However, the device exceeds

TABLE 3. Salient features of Narrowband Internet of Things.

Parameters	Standards of NB-IoT
Organization	3rd Generation Partnership Project (3GPP)
First Release	June 2016
Frequency Spectrum	Licensed
Bandwidth Occupied	180 kHz
Modulation Technique Used	BPSK, QPSK
Frequency Band [53]	700 MHz, 800 MHz, 900 MHz
Downlink Multiple Access Technique	OFDMA
Subcarrier Spacing in Downlink	15 kHz
Slot duration in Downlink	0.5 ms
Uplink Multiple Access Technique (single-tone)	FDMA-GMSK
Uplink Slot duration (single-tone)	2 ms
Uplink Multiple Access Technique (multi-tone)	SC-FDMA
Uplink Slot Duration (multi-tone)	0.5 ms
Subcarrier Spacing in Uplink (single-tone)	3.75 kHz
Subcarrier Spacing in Uplink (multi-tone)	15 kHz
Peak Data Rate (Downlink)	234.7 kbps
Peak Data Rate (Uplink)	204.8 kbps
Payload Size	1600 bytes
Number of Connections Per Cell	around 50,000
Immunity Against Interference	Low
Duplex Mode	Half Duplex
Battery Life [20]	$>$10 years
Latency	$<$10 s
Operation Modes	3
Maximum Coupling Loss Coverage	164 dB
Power Class	23 dBm
Maximum Peak Current	120-300 mA
Sleep Mode Current	5 uA
No.of Antennas	1
Modem Cost	Very Low
Connection Density	1500 km^2
Range	Urban: 1.5 km, Rural: 20-40 km [48]
Messages Per Day	Unlimited
Maximum Downlink Repetitions	2048
Maximum Uplink Repetitions	128
Device Complexity	Low
Handover [9]	No
Authentication Required	Yes
Topology	Star
Voice Support	No
Mobility [44]	Yes
Security	Very High
Power Consumption	Very Low

the limits of the standard LTE coverage (i.e., the device is out of standard coverage of LTE) in level CE1, where the repetition of the packets becomes compulsory. So, the packets must be repeated either by 2, 4, 8 or 16 times. Lastly, the worst channel conditions are experienced in level CE2. Therefore, the data must be repeated by the device up to 128 times. The mechanism by which an NB-IoT device executes the repetition of the IoT messages, is called Hybrid Automatic Retransmission Request (HARQ). In fact, different error detection and correction mechanisms, such as Error Detection (ED), Forward Error Correction (FEC) and Automatic Repeat Request (ARQ) are combined to form the NB-IoT HARQ mechanism, as explained in what follows. Before transmitting each IoT message, the information related to Error Detection and/or Forward Error Correction, is added to each message for detection and correction of errors which are expected to occur. And if there are some errors, assumed to be uncorrectable in the original message,

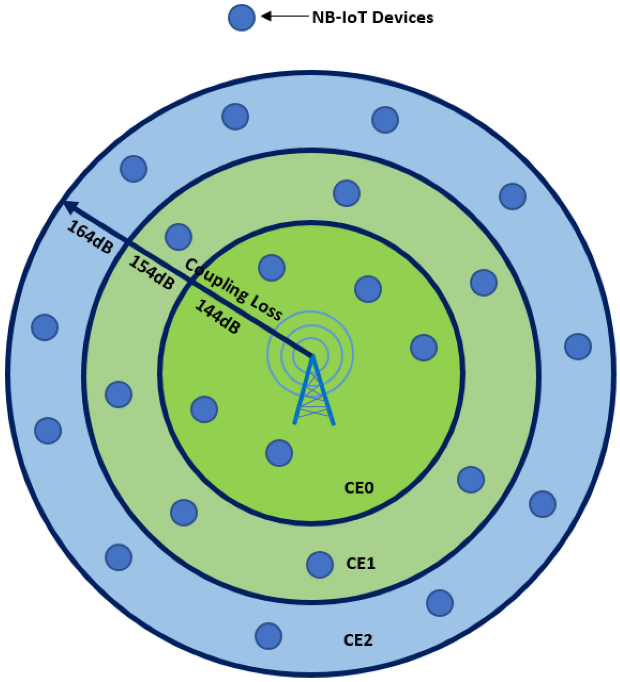

FIGURE 1. Deep Coverage.

ARQ will execute the retransmissions. There are two types of HARQ mechanism: HARQ Type 1 and HARQ Type 2. The rejection of erroneous data frame, its retransmission until its correction and error free reception, is the responsibility of HARQ Type 1 mechanism. It also checks the maximum number of retransmissions allowed. In order to perform the uplink transmission of NB-IoT, the second type of HARQ mechanism is used, which is more sophisticated. In reality, in this type of HARQ mechanism, the information related to ED and FEC is embedded in those data frames, which have to be retransmitted. In fact, embedded ED information and FEC information are alternated by HARQ Type 2 in a data frame which has to be retransmitted. FEC bits are only transmitted on successive retransmissions as per the requirements, i.e., retransmissions will be shorter for devices facing good signal conditions. In this situation, missing of FEC information, will bring about the reduction in the cell capacity, which is considered highly essential for the coverage enhancement. In this context, a repetition factor of 2 is roughly equivalent to a 3 dB gain. Therefore, 128 repetitions result in a 13 dB gain [9]. This gain, added to the 7 dB obtained by increasing power spectral density (PSD) ratio, allows a 20 dB coverage enhancement relative to GSM and GPRS.

B. SUPPORT FOR MASSIVE CONNECTIVITY

NB-IoT has the aim of supporting massive number of connections, i.e., more than 50,000 devices per cell [10], [55], [56]. In NB-IoT, the users can transmit only infrequent, delay tolerant and low data. Therefore, a single cell can cater a huge number of devices simultaneously and a huge network capacity can be achieved by a single NB-IoT carrier. Moreover, the utilization of spectrally efficient transmission scheme in the uplink, helps in achieving high capacity for all those devices, which are facing an extremely limited coverage situation. In this scenario, Shannon's Theorem, regarding channel capacity can be utilized to establish a relationship amongst capacity, desired signal power and bandwidth [37], in a channel having Additive White Gaussian Noise, which is given by the following equation (2).

$$C = W\log_2\left(1+\frac{S}{N}\right) = W\log_2\left(1+\frac{S}{N_0 W}\right) \quad (2)$$

where C represents the channel capacity (bps), S the received signal power and N the received noise power (product of N_0 and bandwidth (W). At extremely limited coverage conditions, when $\frac{S}{N} << 1$, the channel capacity can be represented by the following equation, considering the approximation

$$\ln(1+r) \approx r$$

for $r << 1$, which is given by

$$C = \frac{S}{N_0}\log_2(e) \quad (3)$$

Equation (3) shows the channel capacity when the signal to noise ratio (SNR) is very poor and in this case, the dependency on bandwidth is vanished and channel capacity is only determined by two parameters: the received signal power level and the noise level (N_0). Hence, it can be assumed theoretically that the coverage for a particular data rate is only dependent upon the power level of the received signal, instead of its bandwidth. As the data rate is not scaled down with respect to the allocated device bandwidth at the condition of extremely limited coverage, so the allocation of a small value of bandwidth can be quite advantageous in terms of spectral efficiency for devices facing the worst coverage problem. There are several bandwidth possibilities available for the NB-IoT uplink waveforms. The devices, which are located in the premises of good coverage, a waveform having wide bandwidth, such as 180 kHz, is considered quite advantageous for them. However, the waveforms having small values of bandwidth, can serve the devices, which are facing the problem of poor coverage, more spectrum efficiently. In addition, the uplink of NB-IoT makes use of subcarrier level transmission which allows for a higher utilization level of resources. Moreover, the single-tone transmission of NB-IoT is based on two numerologies (15 kHz and 3.75 kHz). A simultaneous uplink transmission of 48 users can be supported by a single eNB in a 3.75 kHz scheme. Furthermore, NB-IoT has also a simplified signaling overhead as compared to the legacy Long Term Evolution (LTE). The decrement in signaling messages between the user and the eNB, requires less time to release the resources, so that more users can be accommodated.

C. LOW POWER CONSUMPTION

The battery life of NB-IoT devices is more than 10 years [57], which is ensured by 3GPP Resease-13 by introducing two modes: Power Saving Mode (PSM) and enhanced Discontinuous Reception Mode (eDRX) respectively [11], [58], [59]. Both these modes put the NB-IoT devices into the sleep mode, if there is no requirement of any data transmission or reception. With PSM, a long sleep duration of 310 hours can be achieved, which is considered a large power saving. However, this long response time to downlink data arrival in the Power Saving Mode (PSM) makes it unsuitable for applications, such as smart grid and smart metering. Hence, Release-13 had to introduce eDRM, which works in both the states of NB-IoT (idle and connected).

D. REDUCED COMPLEXITY

As the complexity of the NB-IoT devices is directly linked to their cost, simpler structures and network layers have been designed and optimized [12]. In NB-IoT, the number of signals, channels, transceivers and volume of network protocol, have been reduced as compared to the LTE. In addition, NB-IoT has only one transceiver for downlink and uplink transmission. Moreover, as it is intended to support low data rate applications, there is no requirement of high capacity memory. The aforementioned characteristics enable for reduced cost of NB-IoT devices.

E. SPECTRUM REFARMING

Another important objective of NB-IoT is the provision of flexible spectrum migration facilities to the GSM operators and in this context, a small portion of GSM spectrum can be refarmed according to NB-IoT, whereas the LTE carrier supports the deployment of in-band and guardband operations, that will be described in Section V. This preliminary migration, will not bring about spectrum fragmentation and therefore will not hinder the ultimate migration of the complete GSM spectrum to LTE [37]. In this context, a carrier of NB-IoT has already been deployed in the GSM network, which is known as standalone operation mode and after migration of the complete GSM spectrum to LTE, this deployed carrier of NB-IoT (as a standalone mode in the GSM network) can be deployed either as a guardband or in-band within the LTE. The major advantage of this flexibility can be expected in the security of NB-IoT deployments while refarming of LTE to 5G.

F. SECURITY AND RELIABILITY

NB-IoT technology provides an excellent transmission reliability due to its operation in the licensed band. In fact, in the standardization of this technology, the input of the most reliable global carriers was included to maintain the best possible level of reliability. Furthermore, as NB-IoT has been derived from the LTE technology, it is utilizing all the security mechanisms of LTE. This inheritance of reliability and security from the LTE, makes NB-IoT a very reliable and secure technology. For example, the features of authentication, end to end encryption of data and protection of signals etc., present in LTE, can be availed in NB-IoT. Moreover, a very low power consuming protocol, known as User Datagram Protocol (UDP), is used in NB-IoT. The data authentication and decoding are maintained by the cloud server. In addition, the other security measures defined in LTE, can also be utilized in NB-IoT [60].

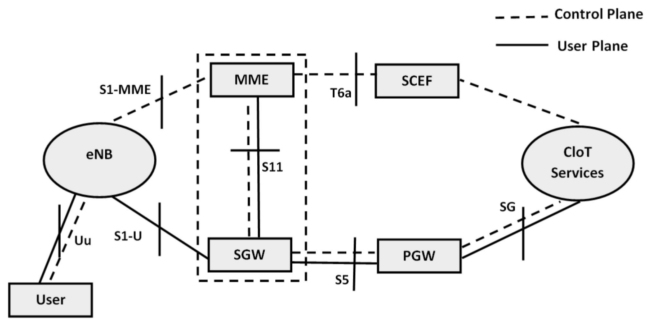

FIGURE 2. Architecture of NB-IoT.

IV. ARCHITECTURE OF NB-IOT

The architecture of NB-IoT is purely inherited from the legacy LTE architecture. Nevertheless, some necessary modifications have been made in the existing architecture of LTE to fulfill the NB-IoT requirements [30], [61]. In this context, Fig. 2 shows a complete block diagram, which illustrates the different NB-IoT key components and their interactions [36], [42], both in the control plane (CP) and in the user plane (UP).

A. COMPONENTS OF NB-IOT ARCHITECTURE

- **NB-IoT User Equipment (UE):** The end device, which interacts and establishes communications with the NB-IoT network [43]. For example, sensors and meters.
- **NB-IoT eNodeB (eNB):** The base station, which is used to manage radio resources and connectivity for User Equipments (UEs).
- **Mobility Management Entity (MME):** It is in fact, a control plane entity and is used to host several functions, such as authentication, authorization, roaming, tracking area list management, particularly for user equipment (UE) in active and idle mode, transfer of warning messages, selection of suitable eNB and lawful interception of traffic signals. In addition, it can also handle mobility management and signaling [62].
- **Serving Gateway (SGW):** This node can be used to route and forward the IP packets. In addition, it also acts as a mobility anchor for the user plane flow during the phenomenon of inter-eNB handovers [63].
- **Packet Data Network Gateway (PGW):** With the help of this node, a seamless connectivity between the NB-IoT and the external networks can be enabled. In addition, it can also provide several important

functions, such as assignment of IP address, session management, data forwarding, and access to the non-3GPP users [12], [64].

- **Service Capability Exposure Function (SCEF):** This node is a new addition to the architecture of NB-IoT. The non-IP data over the control plane is delivered by SCEF. Similarly, the interface for the network services, such as network access capability, authentication and authorization, is provided through SCEF. On the other hand, the conventional architecture of LTE does not have the SCEF node [43].

B. INTERACTION

- **Uu interface:** The NB-IoT user equipment (UE) is connected to the eNB through this interface.
- **S1-MME interface:** The node eNB is linked to the MME via S1-MME interface for control plane signaling.
- **S1-U Interface:** This interface links the node eNB to the SGW for the user plane data transfer.
- **S11 Interface:** The transfer of data between SGW and MME over the control plane is enabled through this newly added interface.
- **T6a Interface:** The connection between MME and SCEF is provided via T6a Interface for the provision of non-IP data services.
- **S5:** It provides connectivity between the Serving Gateway (SGW) and the Packet Data network Gateway (PGW).
- **SG:** The connectivity between the service point and PGW is provided via SG interface

The NB-IoT user data is transferred over the control plane. The eNB receives the user data and then transfers the data towards the MME and SGW. From SGW, the data is moved towards the PGW and finally transferred to the service point. The interface S11, which is connecting the MME and SGW, is a new interface and is not present in the conventional LTE architecture. In order to transfer the data via user plane, the data received at the eNB is transferred to the SGW and then is sent from SGW to the PGW and finally it reaches the service point from the PGW [29].

V. OPERATION MODES OF NB-IOT

There are three types of operation modes supported by the radio interface of NB-IoT [57], [65] as shown in Fig. 3. A brief description of these modes can be presented as follows:

A. IN-BAND MODE OF OPERATION

In this operation mode, shown in Fig. 3(a), NB-IoT is implemented within a single Physical Resource Block (PRB) of the LTE carrier and both the downlink and uplink can share this reserved PRB. The NB-IoT carrier occupies the complete bandwidth of one PRB of the LTE carrier in this mode, i.e., 180 kHz [46]. Moreover, the PRB of LTE carrier allocated to NB-IoT in this mode, can again be utilized by the LTE carrier in the absence of NB-IoT traffic i.e., this PRB can be scheduled by eNB to deal with other traffic of LTE if it is not used for NB-IoT. The details about the allowed PRBs in this operation mode of NB-IoT are provided in Table 4 [31]. The scheduler of eNB can multiplex the traffic of both the NB-IoT and LTE signals. In order to avail the full flexibility of the system, two types of modes are supported by the in-band operation.

- Same Physical Cell ID-In-Band Operation Mode: In this type of in-band operation mode, Cell ID and the number of antenna of NB-IoT and LTE are the same.
- Different Physical Cell ID-In-Band Operation Mode: In this type of in-band operation mode, Cell ID and the number of antenna of NB-IoT and LTE are not the same.

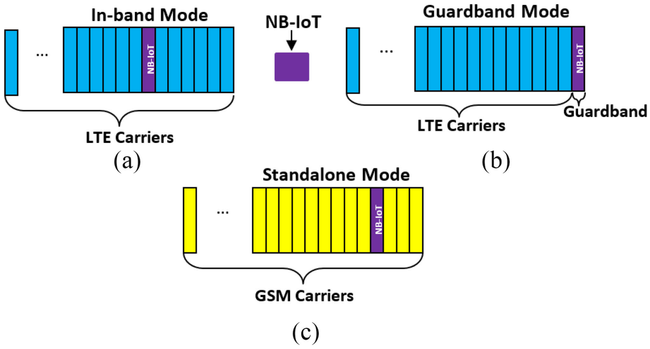

FIGURE 3. Operation Modes of NB-IoT. (a) In-Band Operation Mode; (b) Guardband Operation Mode; (c) Standalone Operation Mode.

TABLE 4. Physical resource blocks (PRBs) allowed in in-band operation mode of NB-IoT.

LTE Bandwidth	Allowed PRBs
3 MHz	2, 12
5 MHz	2, 7, 17, 22
10 MHz	4, 9, 14, 19, 30, 35, 40, 45
15 MHz	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72
20 MHz	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95

B. GUARDBAND OPERATION MODE

In this mode of operation, NB-IoT is implemented in the guardband of the LTE carrier [67], [68] as is shown in Fig. 3(b). So, an LTE carrier can accommodate the carrier of NB-IoT in the PRBs reserved for the LTE guardband. The details about the allowed PRBs in the guardband operation mode of NB-IoT are provided in Table 5. Since there is no need to reserve any LTE data PRB, this mode can present spectrally efficient solutions [6]. Additionally, the impact of interference between LTE and NB-IoT on the uplink of NB-IoT is reduced relative to the in-band mode. Due to capacity limitations, LTE carriers with bandwidths of 1.4 MHz and 3 MHz are not supported, while bandwidth values of 5 MHz and more are supported in this operation mode. In this mode of deployment, the total power of eNB is equally shared

TABLE 5. Physical resource blocks (PRBs) allowed in Guardband operation mode of NB-IoT.

LTE Bandwidth	Allowed PRBs
3 MHz	Not allowed
5 MHz	-1, 25
10 MHz	-2, -1, 50, 51
15 MHz	-4, -3, -2, -1, 75, 76, 77, 78
20 MHz	-5, -4, -3, -2, -1, 100, 101, 102, 103, 104

TABLE 6. Defined values of Guardband bandwidth in different LTE bandwidth standards on each side.

LTE bandwidth	Number of Subcarriers	Guardband Bandwidth
5 MHz	300	250 kHz
10 MHz	600	500 kHz
15 MHz	900	750 kHz
20 MHz	1200	1 MHz

between NB-IoT and LTE and when the power of NB-IoT carrier is increased by using the power spectral density boosting, the total eNB power remains the same.

In addition, the values of guardband bandwidth defined in the guardband operation mode at different bandwidth standards of LTE are presented in Table 6. These values of guardband on each side of the LTE career bandwidth given in Table 6, and can be obtained easily by taking into account that each the subcarrier spacing of 15 kHz [69].

C. STANDALONE MODE OF OPERATION

The third operational mode of NB-IoT is known as the standalone mode of operation, in which an NB-IoT carrier occupies a bandwidth of 200 kHz (i.e., more than 180 kHz), which is similar to a single GSM carrier to facilitate the technology migration [13]. The concept of standalone mode has been illustrated in Fig. 3(c). This operation mode enables coexistence of NB-IoT and GSM for operators after introducing some modifications into the GSM spectrum as adding an extra guardband of 200 kHz between GSM and NB-IoT. Moreover, if the deployment of both the GSM and NB-IoT is done by the same operator, then a guardband with bandwidth of 100 kHz can also be used. Therefore, in order to deploy an NB-IoT to the GSM, in this case, minimum two consecutive carriers of GSM are required to reform [37].

VI. NB-IOT FRAME STRUCTURES

The frame structure of NB-IoT is identical to the LTE frame structure, which consists of a hyper-frame cycle (as is depicted in Fig. 4 and Fig. 5 for uplink and downlink transmission, respectively). In this context, 1024 hyper frames are combined to form a hyper-frame cycle. Similarly, 1024 frames are combined to form one hyper-frame [37], [70]. Furthermore, one frame is composed of 10 subframes, where each subframe has duration of 1ms and is divided into two time slots. This way, the frame duration is 10 ms and the hyper-frame duration is 10.24 s, while the duration of each hyper-frame cycle is approximately 2 h 54 m 46 s. In

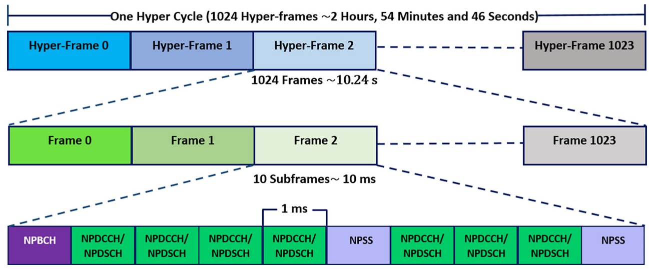

FIGURE 4. Downlink Frame Structure of NB-IoT.

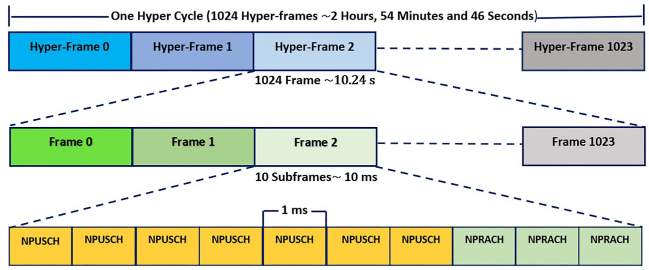

FIGURE 5. Uplink Frame Structure of NB-IoT.

downlink of NB-IoT, there are 12 subcarriers with 15 kHz spacing, where each slot has 7 symbols in the frequency domain. The resource element (RE) is the smallest unit of transmission, one symbol at one of the subcarriers. The uplink of NB-IoT, not only provides support for 15 kHz subcarrier spacing but also for 3.75 kHz. As a result, 7 symbols along with 48 subcarriers obtained. Nevertheless, in this case, the slot duration is increased to 2 ms and each frame is divided into 5 slots.

VII. NB-IOT SIGNALS AND CHANNELS

NB-IoT consists of different downlink and uplink physical signals and channels. A hierarchy of signals and channels used in the downlink and uplink of NB-IoT is shown in Fig. 6. A brief description of these channels and signals is provided in the following sub-sections [9].

A. DONWLINK PHYSICAL SIGNALS AND CHANNELS

NB-IoT provides its support for a set of downlink signals and channels, which are shown in Fig. 6. A time multiplexing is performed of the downlink signals and channels except for Narrowband Reference Signal (NRS), which have their presence in every subframe that carries Narrowband Physical Downlink Shared Channel (NPDSCH) or Narrowband Physical Downlink Control Channel (NPDCCH) or Narrowband Physical Broadcast Channel (NPBCH). The mandatory downlink physical channels are time multiplexed in a period of 20 ms on an anchor carrier of NB-IoT as illustrated in Fig. 7. The subsequent periods will be repeated in a similar pattern. In addition, the transmission of Narrowband Physical Broadcast Channel (NPBCH), Narrowband Primary Synchronization Signal (NPSS), Narrowband Secondary Synchronization

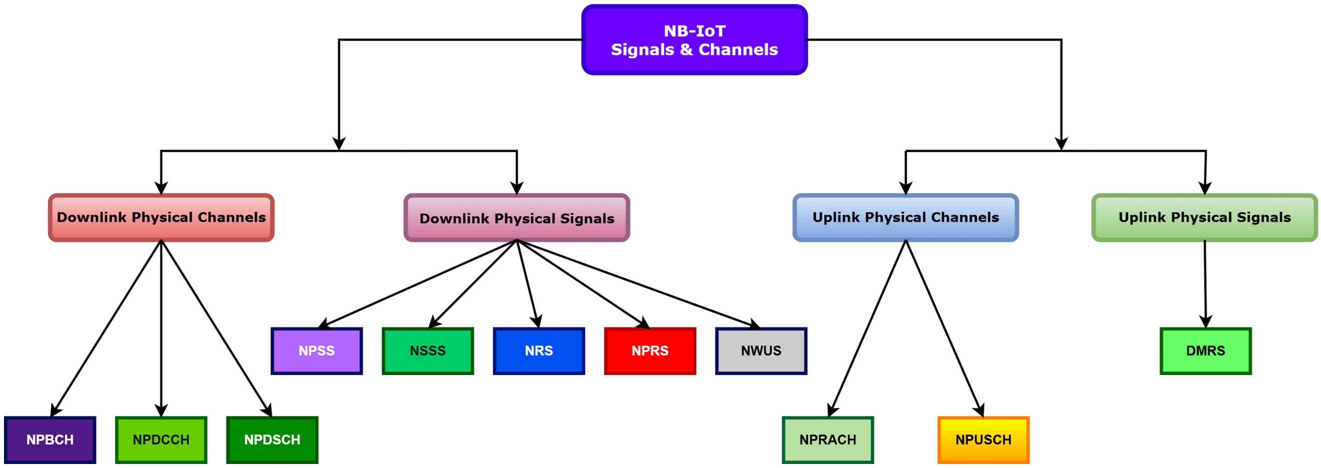

FIGURE 6. Signals and Channels of NB-IoT.

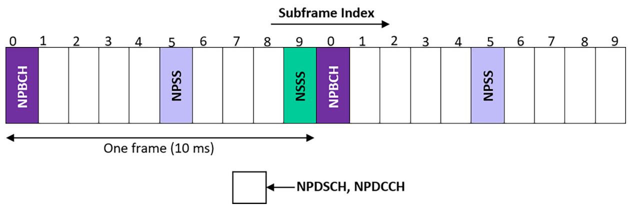

FIGURE 7. Multiplexing of Downlink Physical Channels.

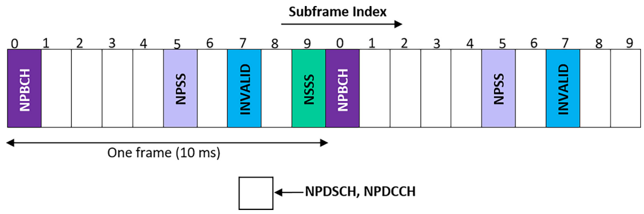

FIGURE 8. DL Channels' multiplexing with Invalid Subframes.

Signal (NSSS) along with some other channels and signals are also shown in Fig. 7. It can clearly be seen from Fig. 7 that the transmission of NPBCH and NPSS will be performed in subframe 0 and 5 of every frame respectively. Similarly, NSSS will be transmitted in subframe 9 of any other frame. Furthermore, NPDCCH or NPDSCH can be transmitted in the remaining subframes. NB-IoT provides its support for a set of downlink signals and channels, which are depicted in Fig. 6. There are also some subframes which neither carry NPBCH, NPSS nor NSSS, and are called invalid subframes. These invalid subframes are not considered as part of NB-IoT subframes and while mapping the transmissions of NB-IoT NPDCCH and NPDSCH onto the subframes, these invalid subframes are skipped by any downlink monitoring device. While implementation of NB-IoT inside a carrier of LTE with Multimedia Broadcast Service Single Frequency Network (MBSFN) subframes, the concept of subframe invalidity is very significant. All the PRBs of LTE carrier are used by an MBSFN subframe and there is no availability of the resource elements for NB-IoT in the subframe. During the implementation of NB-IoT into the guardband of LTE carrier having MBSFN subframes configurations, the notion of subframe invalidity is also very useful. In fact, the subframe structure of an MBSFN subframe is entirely different from a regular subframe. As a result, the confirmation of coexistence performance of NB-IoT and LTE carrying MBSFN subframes, becomes very difficult on the adjacent PRBs because the length of the cyclic prefix of an MBSFN subframe is longer than the normal cyclic prefix length. Hence, the duration of OFDM symbol observed is quite different as compared to the OFDM symbol duration used for NB-IoT. Therefore, the MBSFN subframes of LTE can be declared as invalid for NB-IoT and there is no need of transmitting the downlink signals of NB-IoT into these subframes. For example, subframe 7 has been declared as invalid as shown in Fig. 8. This subframe is unavailable for both data and control channels (NPDSCH or NPDCCH). Next, the different NB-IoT signals and channels will be described.

- **Synchronization Signals (NPSS/NSSS)**: The synchronization of a device to an NB-IoT cell can be achieved by NPSS and NSSS [71], [72]. As depicted in Fig. 9, these signals are transmitted on the basis of a repetition interval of 80 ms in certain subframes. The identification of frame-related information and the detection of the cell identity number within the 80 ms repetition interval of NPSS and NSSS can be performed after the synchronization of the NB-IoT device to the NPSS and NSSS. A unified synchronization algorithm can be used by the device with the help of NPSS and NSSS without having knowledge of the operation mode of NB-IoT during initial acquisition and in order to achieve this, collision with REs must be avoided as much as possible. For instance, when it is required to perform numbering of subframes (0-9) within a frame,

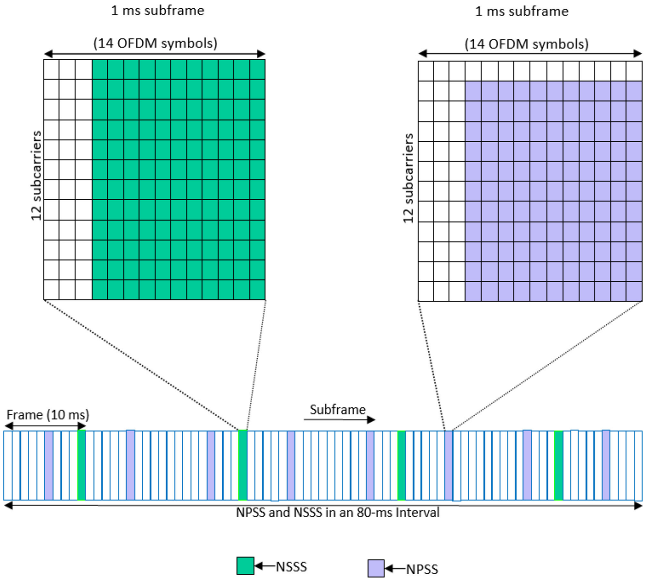

FIGURE 9. Transmission of NPSS & NSSS within a Repetition Interval of 80ms.

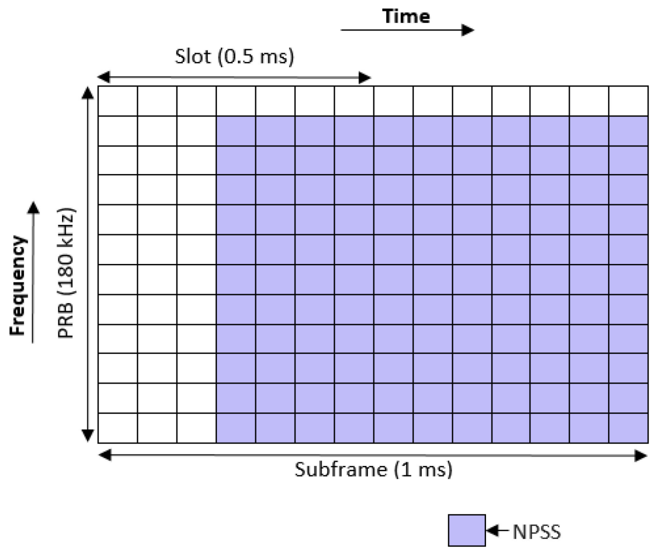

FIGURE 10. Mapping of NPSS.

TABLE 7. Characteristics of NPSS.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Carrier	Anchor
Subframe	5
Subframe Periodicity	10 ms
Sequence Pattern Periodicity	10 ms
Basic transmission time interval (TTI)	1 ms

TABLE 8. Characteristics of NSSS.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Carrier	Anchor
Subframe	9
Subframe Periodicity	20 ms
Sequence Pattern Periodicity	80 ms

there is a strong possibility of the utilization of any of the subframes (1, 2, 3, 6, 7 and 8) as an MBSFN by the LTE. Nevertheless, the device is unaware of the operation mode during the initial cell acquisition. The possibility of collision with MBSFN subframe of LTE can be reduced if the subframe 5 is used for NPSS and the subframe 9 for NSSS. Moreover, the first three symbols of OFDM may be used by LTE for control-channel information in every subframe. Therefore, for collusion avoidance the first three OFDM symbols are not used in those subframes which carry either NPSS or NSSS.

- **Narrowband Primary Synchronization Signal (NPSS)**: This signal provides time and frequency synchronization of devices to NB-IoT cells. Its mapping within the time-frequency grid of NB-IoT is shown in Fig. 10. Although the synchronization information related to the subframe is obtained by NPSS, the information regarding Physical Cell Identity (PCID) is not obtained by NPSS. NPSS must be detectable even at high values of frequency offset. The standard parameters required for the NPSS are shown in Table 7.
- **Narrowband Secondary Synchronization Signal (NSSS):** When a device acquires the NPSS, it performs time and frequency synchronization and after the synchronization, it switches to NSSS for the detection of cell identity and acquiring further information related to the frame structure. The cell identity is identified unambiguously by a device with the help of NSSS. The transmission of NSSS is performed in the 9th subframe of every frame and this process is repeated after every 20 ms. Symbols 3 to 13 of the NB-IoT OFDM grid and all subcarriers are used by NSSS, as shown in Fig. 11. The NSSS sequence can be generated using a frequency domain length 131ZC. There are 504 unique Physical Cell Identities (PCIDs) supported by NB-IoT and these PCIDs are indicated by NSSS. The important parameters required for the NSSS can be found in Table 8.
- **Narrowband Reference Signal (NRS):** The NRS is a signal by which the downlink channel coherent demodulation, channel estimation [31], quality and signal measurements can be performed. This signal is mapped to those subcarriers that are present in the last two symbols of OFDM in each slot of a subframe, which carries any of the data-related channels (NPDSCH, NPBCH or NPDCCH) as displayed in Fig. 12. However, it can also be transmitted in those

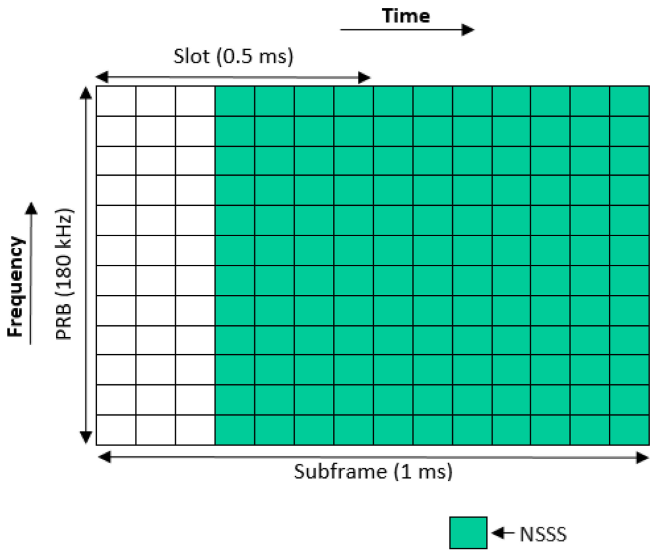

FIGURE 11. Mapping of NSSS.

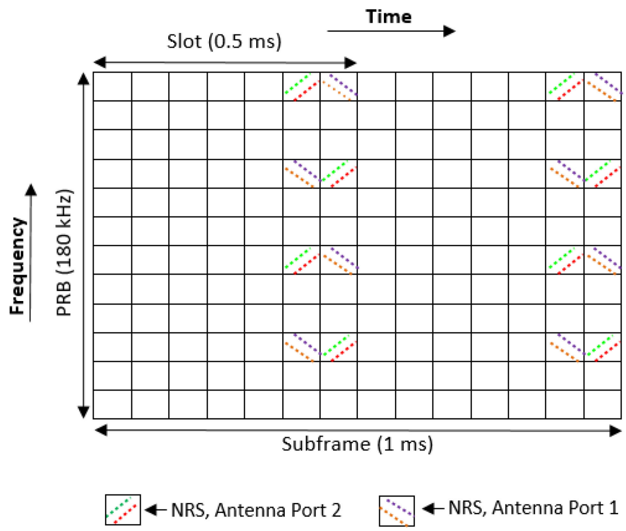

FIGURE 12. Mapping of NRS in a subframe.

subframes that are without any scheduled NPDCCH or NPDSCH. Moreover, NRS is transmitted in all the subframes that are not dedicated to the synchronization signals (NPSS, NSSS). However, devices must be able to differentiate the subframes, which carry NRS for the downlink measurement and channel estimation. The standard parameters used for the NRS are presented in Table 9.

- **Narrowband Physical Broadcast Channel (NPBCH)**: NPBCH delivers the Master Information Block (MIB) of NB-IoT. An MIB provides all the necessary information for the device to operate in the network of NB-IoT. This channel is transmitted in the subframe 0 of every radio frame. There are 8 blocks, in which an MIB-NB is divided. Every block is transmitted 8 times. Therefore, each MIB-NB has 64 transmissions. In addition, a transmission time interval (TTI) duration of 640 ms is used by NPBCH. The number of REs present in a subframe for NPBCH is 100, and the digital modulation technique used is QPSK. Therefore, an NPBCH subframe carries 200 encoded bits. The number of transport-blocks (TBS) bits for NPBCH is 34. The transport block (TB) of an NPBCH is attached to the Cyclic Redundancy Check (CRC) that is masked with a sequence depending on the number of antenna ports 1 or 2 of NRS, as is shown in Fig. 13. In this way, the number of antenna ports of NRS can be detected via blind decoding. The main parameters related to NPBCH are provided in Table 10.

TABLE 9. Characteristics of NRS.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Carrier	Any
Subframe	Any
Basic TTI	1 ms
Sequence Pattern Periodicity	10 ms

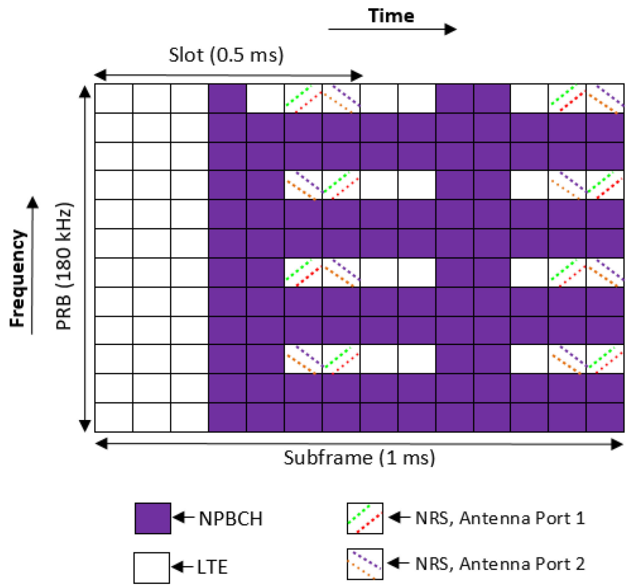

FIGURE 13. Mapping of NPBCH.

TABLE 10. Characteristics of NPBCH.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Modulation	QPSK
Carrier	Anchor
Subframe	0
Basic TTI	640 ms
Periodicity	10 ms

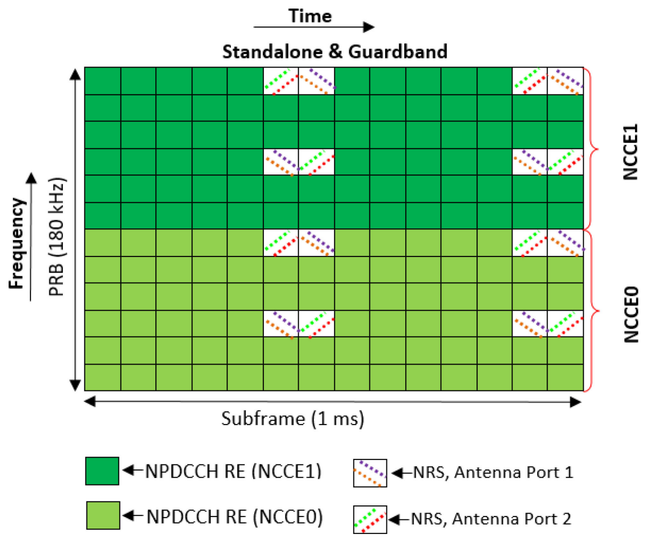

FIGURE 14. Mapping of NPDCCH in Standalone & Guardband Operation Mode of NB-IoT.

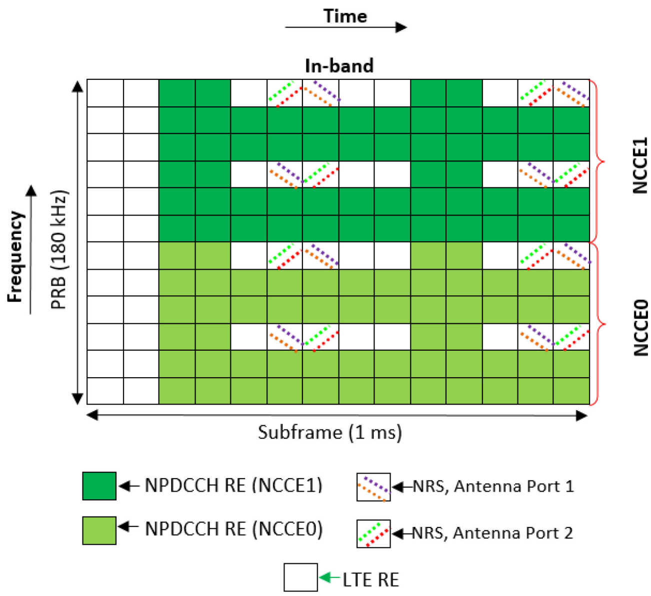

FIGURE 15. Mapping of NPDCCH in In-band Operation Mode of NB-IoT.

TABLE 11. Characteristics of NPDCCH.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	90/180 kHz
Carrier	Any
Subframe	Any
Basic TTI	1 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128, 256, 512,1024, 2048

- **Narrowband Physical Downlink Control Channel (NPDCCH)**: NPDCCH is used to carry the scheduling information for downlink and uplink. The digital modulation technique used by NPDCCH is QPSK. There are three types of information by which a device can monitor an NPDCCH channel. These information include DCI format N0 (uplink grant information), DCI format N1 (NPDCCH order, downlink scheduling information and notification regarding any changes in the multicast control channel) and DCI format N2 (SI update, paging indications, and scheduling or notification regarding any updates in multicast control channel). The number of bits in the DCI formats N0, N1 and N2 are: 23, 23 and 15, respectively. The information bits present in the DCI are used to generate 16 Cyclic Redundancy Check (CRC) bits. These CRC bits are not only used for error detection but also for differentiating the information contained in each DCI format.
  In addition, these CRC bits can also identify a device for which the DCI is intended. In order to achieve this, the CRC bits are scrambled on the basis of different radio network temporary identifiers (RNTIs). A single subframe of NPDCCH consists of two Narrowband Control Channels Elements (NCCEs): NCCE0 and NCCE1 as shown in Figs. 14 and 15 respectively, in which the NPDCCH mapping for the standalone, guardband and in-band NB-IoT operation modes are depicted. The lowest six subcarriers are taken by NCCE0 and the highest six subcarriers are taken by NCCE1. The availability of resource elements (REs) within one NCCE is dependent upon the logical antenna ports numbering and deployment modes of NB-IoT, however, in the case of in-band operation, another parameter is further extended, which is the LTE cell configuration. The mapping of NPDCCH REs in the NPDCCH subframe can be received and used by NB-IoT devices only after the acquistition of the System Information (SI) and the cell selection. The mapping of NPDCCH to the first few OFDM symbols of a subframe is avoided in the in-band operation mode and in this way the LTE downlink (DL) control region can be avoided. The LTE downlink control region size is considered very important because the starting OFDM symbol index is entirely depended upon the size of the control region of LTE downlink and the device is signaled about this size. The significant parameters along with their standard values, required for the NPDCCH are shown in Table 11.
- **Narrowband Physical Downlink Shared Channel (NPDSCH)**: The transmission of downlink data is performed by NPDSCH, illustrated in Fig. 16. In addition, NPDSCH also carries the system information, user data and paging message. Also, the transmission of unicast data is one of the functionalities of this channel. Broadcast information, such as SI messages, are also transmitted with the help of NPDSCH. The segmentation of a data packet received from higher layers, can be performed into one or more transport blocks (TBs) but only one transport block (TB) is transmitted by NPDSCH at a time. The digital modulation technique adopted by NPDSCH is QPSK.

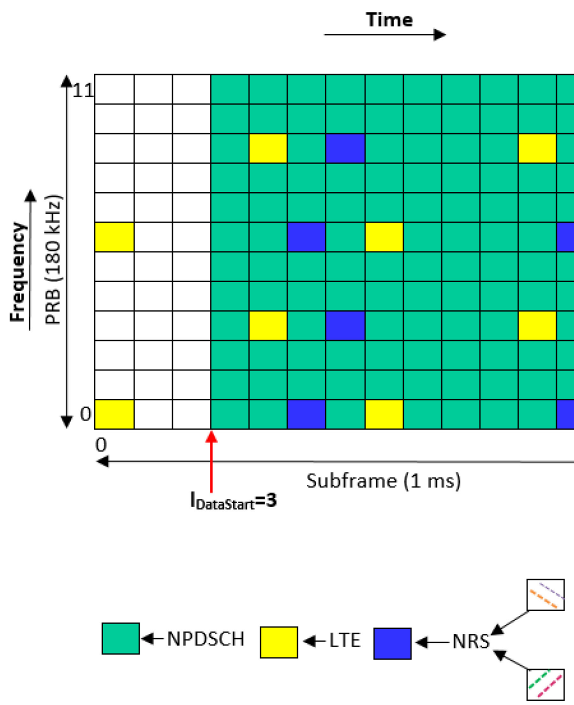

FIGURE 16. Mapping of NPDSCH.

TABLE 12. Characteristics of NPDSCH.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Modulation	QPSK
Carrier	Any
Subframe	Any
Basic TTI	1, 2, 3, 4, 5, 6, 8, 10 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, 2048

Likewise, a transport block (TB) size with upto 680 bits is supported by NPDSCH. Moreover, there are a number of subframes of NPDSCH, within which a TB can be mapped. Similarly, NPDSCH uses LTE Tail-Bit Encoding (TBCC) as a code for forward error correction. Table 12 displays the important parameters used for the NPDSCH.

- **Narrowband Positioning Reference Signal (NPRS)**: It is a broadcast signal and is introduced by 3GPP in its release 14 and displayed in Fig. 17. The positioning accuracy of an NB-IoT device can be improved by this signal [73]. It enables to estimate the positioning of a device by the observation of the arrival time difference. Unlike the signals that are configured by Radio Resource Configuration (RRC), NPRS signals are configured by the LTE Positioning Protocol (LPP). LPP is a device specific protocol and is carried between a positioning server (Evolved Serving Mobile Location Center) and the device. The negotiation about NPRS configuration between the positioning server and a base station is carried out via LPP protocol [74]. The significant parameters along with their standard values, required for the NPRS are shown in Table 13.

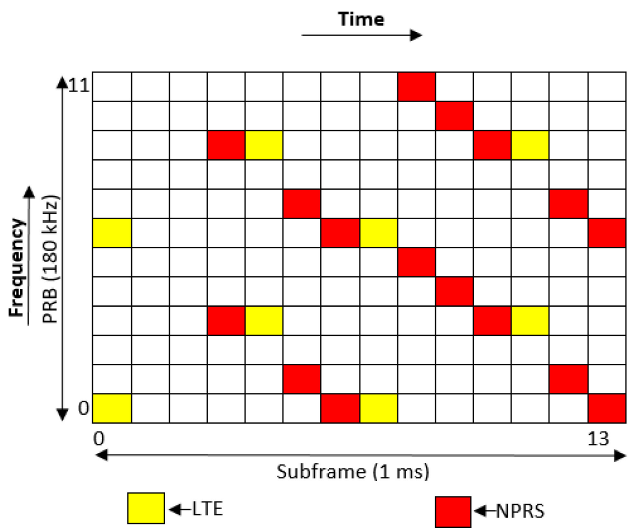

FIGURE 17. Mapping of NPRS.

TABLE 13. Characteristics of NPRS.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Carrier	Any
Subframe	configured by LPP
Basic TTI	1 ms

- **Narrowband Wake Up Signal (NWUS):** This signal was introduced in Release 15 by 3GPP and can be used to enhance the energy efficiency of a device. Also, it allows for the reduction of the number of paging queries monitored by NB-IoT devices when the paging signals are required infrequently. However, NWUS is an optional feature and eNB can enable or disable it as required. A Zadoff–Chu (ZC) sequences with a length of 132 REs is used for NWUS, so that a signal with high reliability can be generated, minimizing the mis-detection rate [31]. In guardband and standalone NB-IoT operation modes, the 3 first OFDM symbols are used for NWUS, while in in-band operation mode, NWUS is mapped into the last 11 symbols. The important parameters required for the NWUS are presented in Table 14.

B. UPLINK PHYSICAL CHANNELS AND SIGNALS

NB-IoT consists of the following uplink physical channels and signals, that are described in the next sections.

- **Narrowband Physical Random Access Channel (NPRACH)**: A device can initiate a connection in NB-IoT by the NPRACH. This channel allows for the estimation of the time of arrival (ToA) of the received

TABLE 14. Characteristics of NWUS.

Parameters	Standard Values
Subcarrier Spacing	15 kHz
Bandwidth	180 kHz
Carrier	Any (for paging)
Basic TTI	1 ms

TABLE 15. Characteristics of NPRACH.

Parameters	Standard Values
Subcarrier Spacing	3.75 kHz
Bandwidth	3.75 kHz
Carrier	Anchor
Subframe	Any
Basic TTI	5.6/6.4 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128

TABLE 16. Characteristics of NPUSCH.

Parameters	Standard Values
Subcarrier Spacing	3.75, 15 kHz
Bandwidth	3.75, 15, 45, 90, 180 kHz
Carrier	Any
Subframe	Any
Basic TTI	1, 2, 4, 8, 32 ms
Repetitions	1, 2, 4, 8, 16, 32, 64, 128

signals, so that the roundtrip propagation delay between each device and the base station can be obtained. As the transmission scheme used by the uplink of NB-IoT is either Single Carrier Frequency Division Multiple Access (SCFDMA) or single-tone transmission with CP, the signals received from the multiple devices must be aligned to preserve the orthogonality between the different devices that have been frequency division multiplexed. The estimation of ToA helps the base station in determining the timing required for the alignment of the signals received from each device. In addition, the designing of NPRACH preamble targets a waveform that is time continuous and has peak to average power ratio (PAPR) nearly equal to 0 dB [37]. The significant parameters required for the NPRACH are summarized in Table 15.

- **Narrowband Physical Uplink Shared Channel (NPUSCH):** The functionality of NPUSCH is to carry the user data related to the uplink or control information received from higher layers and the HARQ acknowledgement necessary for transmission of NPDSCH. Moreover, by using NPUSCH, a device can initiate a scheduling request. This is a feature that has been introduced by 3GPP Release 15. The significant parameters required for the NPUSCH are summarized in Table 16. The principle of NPUSCH waveform is the same as is adopted by the waveform of LTE SCFDMA. The mapping of NPUSCH is shown in Fig. 18.

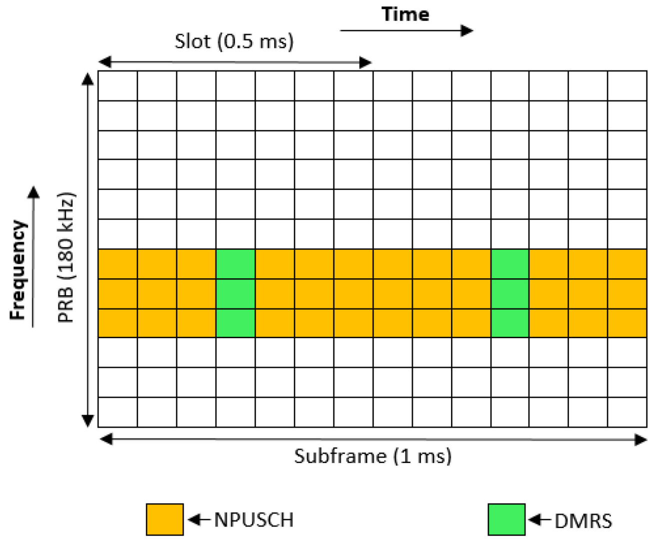

FIGURE 18. Mapping of DMRS and NPUSCH.

- **Demodulation Reference Signals (DMRS):** In order to perform channel estimation for uplink transmission in the frequency domain, DMRS is used. It is also called Uplink Pilot [31]. DMRS and NPUSCH are always associated with each other, as is depicted in Fig. 18. Therefore, DMRS is transmitted in every slot of NPUSCH and they both have identical bandwidths [37]. In addition, DMRS sequences of LTE, allocated for one PRB, are reused as DMRS of NB-IoT with bandwidth of 180 kHz [75].

VIII. APPLICATIONS OF NB-IOT

The success and establishment of NB-IoT applications, as those of any LPWAN technology, rely on the ability of NB-IoT to enable cost-effectiveness, low power consumption and massive deployment. On the other hand, high data rates have not been a priority by most of the applications. In this context, the requirements of connectivity of many applications of IoT for consumer markets as well as industries are perfectly matched with the capabilities of the NB-IoT networks. The applications in which NB-IoT can be deployed are Smart Cities, Smart Homes, Health Care, Fitness Trackers, Smart Factories, Asset Trackers, Agriculture, Smart Grids and Predictive Maintenance, etc. There is an extensive list of NB-IoT use cases and it is growing continuously [76]. In this context, Fig. 19 shows schematically some of the most prominent applications of NB-IoT, which are described below.

- **Smart Cities**: NB-IoT can be extensively used in the development of smart cities because a huge number of interconnected IoT devices are involved in this future technology [77]. The services of NB-IoT can be utilized in the smart traffic management, smart waste management, monitoring of air quality and in the public facilities, such as electricity meters and to control street

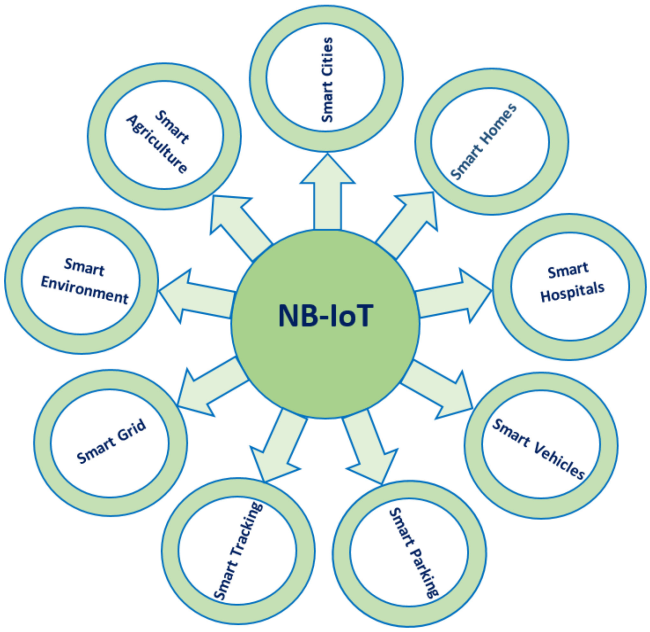

FIGURE 19. Smart Applications.

light systems to save energy and cost. In addition, NB-IoT can also be used in the deployment of automatic garage systems by utilizing deep learning techniques, which can save the material resources and cost by providing inexpensive solutions [78].

- **Smart Vehicles:** Internet of Vehicles (IoV) is an example of the applications of NB-IoT to smart vehicles [79], [80]. The use of NB-IoT devices in the vehicles, helps in accessing information regarding real time traffic. In this way, speed of the vehicles can be controlled by sending warning instructions on overspeeding to the drivers. Thus, safety can be provided to the drivers by avoiding congestions and accidents.
- **Smart Parking:** Due to increasing population and the intensive usage of vehicles, parking has become the most serious challenge for the biggest cities. However, NB-IoT along with different networks based on wireless sensors, can provide better solutions to deal with the issues of parking [22], [81]. In this context, several companies, such as Mediatek, Huawei, Qualcomm and Ericsson are continuously working to resolve the problem of parking by developing smart parking solutions [82]. In the smart parking system, information regarding traffic congestion and service distribution are characterized and parking space is searched rapidly to provide a better parking management.
- **Smart Homes**: NB-IoT applications can also be seen in the smart homes [83]. For instance, home security, live chat, smart metering and management of energy consumption etc. In smart metering, manpower can be reduced by collecting data automatically and remotely through the NB-IoT network. Moreover, NB-IoT can also be used in the indoor environment through the remote monitoring systems [84] for home-related parameters such as temperature, humidity and light intensity.
- **Smart Hospitals**: In the hospitals, a number of smart devices and infrastructures, e.g., outpatient clinic, intelligent monitoring center, pharmacy etc., have been introduced, thanks to the emergence of NB-IoT. These smart devices can be connected with each other through the NB-IoT network. There are two scenarios, in which the paradigm of smart hospital works [23]; the first one is the clinical care, in which the patient is admitted in the hospital and in the second scenario, the patient is monitored and treated remotely through the remote care. In this context, the heart beat, blood pressure and temperature etc., are monitored remotely. Nevertheless, NB-IoT is not fully applicable for the health care purpose because NB-IoT has several challenges which include privacy, data security, hospital security, high cost and most importantly the high latency factor, by which the accuracy and reliability of data are affected stringently. Nonetheless, despite all the mentioned factors, NB-IoT can be used in the monitoring and keeping a track of the health of the patients [11], [24], [85].
- **Smart Logistics and Tracking**: The use of NB-IoT devices is also increasing in logistics and tracking of objects [25]. The NB-IoT devices can be used in the real time tracking of objects' position/location and precise information of their delivery. In this regard, smart tracking tags based on NB-IoT network, have been launched by Samsung to track objects Intelligently.
- **Smart Agriculture**: NB-IoT has also interesting applications in agriculture [86], [87]. To grow the maximum yield at reduced input and production costs, is a main objective of every agricultural farm [65]. In this context, water can be utilized expeditiously for the purpose of irrigation. In this context, different soil moisture sensors are installed in the farm to collect data and to transfer it to the cloud of NB-IoT via the NB-IoT base station. The received data can be processed through different deep learning algorithms by which a farm can be divided into different zones with respect to the moisture contents present in the soil. The required quantity of water is transferred for a particular time with the help of a water control NB-IoT device. Moreover, the zones, which have an adequate level of moisture in their respective sensor nodes, are entered into the sleep mode. In this way, water and energy can be utilized more efficiently.
- **Smart Environment**: NB-IoT can help to safeguard the environment from pollution and degradation by monitoring and controlling the factors like air and water quality, soil contamination, and waste management and protecting the endangered ecosystems and individuals. For example, monitoring and controling of water level in some industries to reduce its consumption and wastage [26], [88]. Also, in rural areas of Malaysia,

for instance, water monitoring systems based on NB-IoT are gaining widespread recognition [89]. Similarly, the air pollution and air quality can be monitored by detecting the pollution index through smart sensors that use the NB-IoT network for transmission of data [90], [91]. Moreover, NB-IoT solutions can also be useful in the wildlife tracking. Thus, monitoring of environment, animal diseases [92] and endangered species conservation can be achieved by utilizing the NB-IoT solutions, and are otherwise highly challenging tasks.

- **Smart Grid**: As NB-IoT technology has the features of deep coverage, low power and support for huge number of connections, it can be applied as solution for smart grid communications. A long range communication with high reliability and appropriate throughput can be achieved through NB-IoT technology [93]. However, due to some particular constraints, NB-IoT is not fully appropriate for this application. For example, it has high latency; therefore, it cannot be used for real time applications. The optimization of NB-IoT can be done to provide outrage restoration [94]. Similarly, in smart grid, the management message can be delivered during power outage. Nevertheless, on time message delivery and reliability must be confirmed.

In general, there are many organizations which have extensively adopted NB-IoT in different use cases because it is considered as the best choice for the applications of IoT. NB-IoT has brought about many positive changes in the people's lives [9].

IX. QUALITY OF SERVICE (QOS) CHALLENGES

The devices used for NB-IoT are typically very small, and the advantage of their low cost is counterbalanced with limited QoS capabilities. The design of NB-IoT does not fully support applications requiring high bandwidth, such as gaming or video streaming. On the other hand, only delay tolerant applications are supported by NB-IoT [12]. The following factors can be attributed to the insufficient support of QoS in NB-IoT devices.

- **Latency**: NB-IoT technology is solely suitable for delay tolerant applications and is not designed for real time monitoring. Because of this limitation, NB-IoT is not a fully developed solution for smart grid systems owing to the inability of transmitting the real time information in emergency conditions, such as system instability or fault events, etc [95]. Likewise, NB-IoT is not able to cope with some of the scenarios expected in smart hospitals because there are plenty of parameters, which require their real time monitoring with low latency [28]. Therefore, it is necessary to investigate the best techniques to reduce NB-IoT latency down to levels acceptable for these applications.
- **Coverage Restriction:** The unavailability of the LTE network in the rural areas will prevent the application of NB-IoT to herd management, wildlife tracking and smart farming [92]. So, in order to meet the stringent requirements of both critical and massive IoT applications, the availability of an excellent coverage is imperative [96].
- **Mobility Management**: NB-IoT technology offers limited support for mobility upto 3GPP Release 15, but NB-IoT users can not avail the feature of explicit handover because in the failure of the procedures of Radio Resource Control (RRC) connection resumption and re-establishment, the NB-IoT user has to connect again to the network. As a result, the battery life of the device is decreased. There are many scenarios, which necessitate mobility support, such as smart goods tracking, smart vehicles, wildlife tracking, and remote patient monitoring if the patient is moving fast, etc. In fact, NB-IoT can support only low speed mobility and encounters communication latency which immediately interrupts the switching phenomenon between the gateways [92]. Owing to the insufficient mobility support, the optimization of the cell reselection performance becomes crucial to facilitate NB-IoT service consistently. In [91], the authors have provided a methodology for the cell reselection of NB-IoT. Simulation results [97] show that an improved mobility performance can be achieved through the shorter reselection timer and paging DRX (Discontinuous Reception), at the cost of high battery consumption. So, there is a trade-off between the extent of the mobility support and the device battery consumption.
- **Half Duplex FDD**: Until the publication of 3GPP Release13 and 14, the only duplex mode supported in NB-IoT was half duplex Frequency Division Duplex (FDD) [98], which meant that NB-IoT user equipment (UE) was unable to utilize the full available spectrum. Hence, the maximum data rate and throughput transmitted by the UE was reduced. In contrast to NB-IoT, both FDD and TDD were supported in legacy LTE for the downlink and uplink transmissions [99], what allows for high throughput in both directions. Nevertheless, Time Division Duplexing (TDD) mode was included in 3GPP Release 15, both for the downlink and uplink data transmission to fully utilize the available spectrum. In fact, although the introduction of TDD to NB-IoT delivered significant advantages, there are also a few drawbacks linked with TDD support [15]. For example, TDD-based NB-IoT networks bring about interferences to FDD-based LTE networks and even TDD-based LTE networks in the guardband and in-band NB-IoT operation modes. In addition, there might be periodicity mismatches of NPBCH, NPSS and NSSS with the downlink subframe configuration of TDD-based LTE [15] during the configuration of the parameters of any TDD-based NB-IoT network.
- **Security:** In NB-IoT systems, security is also considered as one of the major concerns. In fact, the

architecture of NB-IoT technology is considerably simple, and the available resources, such as battery power and bandwidth, are limited. Owing to these factors, it is quite challenging for the NB-IoT devices to support the complex security algorithms at the layers of the network [100]. Moreover, the use of NB-IoT networks in device-to-device (D2D) communications can bring about the eavesdropping problem and malicious nodes may attack the devices [101]. Therefore, it is highly necessary to fix the security risks before using the NB-IoT devices in applications involving D2D communications.

- **Limited Data Rate:** NB-IoT has quite limited data rate at the Physical layer (PHY) because only one resource block can be assigned in the downlink. Similarly in the uplink, only one resource unit is assigned. Therefore, both the UL and DL data rates are limited to hundreds of kbps. Moreover, transport block repetitions and overhead further reduce the PHY data rate as the different services and applications utilize this data rate at the application layer [12].
- **Transmission Diversity**: Transmit diversity Implementation at the base station can enhance the detection probability of the NB primary (NPSS) and secondary (NSSS) synchronization signals, without adding computational burden to the user equipment (UE). Only up to two antennas are supported by NB-IoT UE [31], [102] for the transmission diversity in the downlink. In contrast, multiple antennas can be used by the legacy LTE devices for the purpose of transmission and reception at the downlink and uplink. For instance, eight antennas can be supported by an LTE device. Due to this characteristic, the user equipment can transmit and receive a huge number of packets, which results in a significant enhancement in reliability. In [102], authors investigate how using precoding vector switching (PVS) based transmit diversity with up to eight transmitting antennas impact the detection probability of the physical cell ID (PCID) in NB-IoT systems. The outcomes of the simulations, revealed that PVS-based transmit diversity enhanced detection probability of PCIDs in NB-IoT networks considerably. The detection probability improved by approximately 14%, while using 4 antennas instead of 2, when fading was uncorrelated. Simulation results show that deployment of eight antennas instead of four, can bring about an extra 8% detection probability improvement during circumstances, where both frequency offset reached 70 kHz and antenna signals experienced correlation. In this way, capabilities of transmission diversity in actual implementation environments are verified.
- **Channel Quality Indicator (CQI)**: LTE devices send the so-called channel quality indicators (CQI) to the eNodeB on the uplink, and in this way, a report based on the conditions and downlink channel quality is provided to the eNodeB through the uplink. Similarly, there are some physical layer measurements, which are known as channel measurements, and are performed to take handover decisions. On the other hand, the transmission of CQI [27], [40] and measurements regarding handover decisions and mobility are not supported by NB-IoT user equipment, which further reduces the best achievable throughput and data rate.

X. CONCLUSION

Low power wide area network (LPWAN) technologies are playing an important role to cater the requirements of a large number of connected IoT devices and bring about the rapid growth of IoT applications globally. In this paper, a comprehensive review on NB-IoT in comparison with other LPWAN technologies, such as Sigfox and LoRa, has been provided to reveal its significant potential. The analysis shows that although NB-IoT is not a suitable choice for the long range communications as compared to both Sigfox and LoRa, it is considered the best option for all those applications, which require higher level of Quality of Service (QoS). NB-IoT can provide the highest date rates and payload length, reduced latency, less interference, improved battery life, reduced complexity, good coverage and localization by using a licensed spectrum of existing LTE. Furthermore, the main objectives and the key features of NB-IoT have also been discussed in detail. In addition, the architecture of NB-IoT network has been described, differentiating the three operation modes that provide deployment flexibility of NB-IoT in combination with other networks. Downlink (DL) and uplink (UL) NB-IoT frame structures have been analyzed and a comprehensive description of the DL and UL physical signals and channels along with their functionalities has been presented. Additionally, a detailed review on some of the most prominent applications of NB-IoT has been provided. Finally, some of the most crucial challenges regarding QoS of NB-IoT, have been highlighted in this paper. By taking into account these serious constraints, the open research lines have been outlined suggesting that NB-IoT technology still needs some improvements to be successfully used in some applications. Nevertheless, regardless of these significant challenges, NB-IoT is expected to play a pivitol role in the future communications by providing its valuable features and services for IoT networks.

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MUHAMMAD WASEEM received the bachelor’s degree in electronic engineering from the Sir Syed University of Engineering & Technology, Karachi, Pakistan, in 2008, and the master’s degree in telecommunications engineering from the University of Sunderland, U.K., in 2011. He is currently pursuing the doctoral degree with the Department of Electronic and Communications Engineering, University of Zaragoza, Spain. He joined the Department of Telecommunication Engineering, Sir Syed University of Engineering & Technology as an Assistant Professor in June 2011, where he served for 10 years. Since March 2024, he has been serving as an N3 researcher with the University of Zaragoza. His research interests include NB-IoT, cellular communications, and optical communications and in particular the applications of plastic optical fibers as the media for the short range communication networks.

ALICIA LOPEZ received the M.Sc. degree in communications engineering and the Ph.D. degree from the University of Zaragoza (UZ), Zaragoza, Spain, in 2002 and 2009, respectively. In 2002, she joined the Photonic Technologies Group, Aragon Institute of Engineering Research, UZ, where she has been with the Department of Electronic Engineering and Communications since 2004 and is currently an Associate Professor. Her research interests include the use of plastic optical fibers in communication applications and the design and evaluation of optical networks.

PEDRO LUIS CARRO (Fellow, IEEE) was born in Zaragoza, Spain, in 1979. He received the M.S. and Ph.D. degrees in telecommunication engineering from the University of Zaragoza, Zaragoza, Spain, in 2003 and 2009, respectively. In 2002, he carried out the Master thesis on antennas for mobile communications with Ericsson Microwave Systems, AB, Gothemburg, Sweden. From 2002 to 2004, he was with Rymsa S.A., where he was with the Space and Defense Department as an Electrical Engineer. From 2004 to 2005, he was with TELNET Redes Inteligentes in the Research and Development Department as an RF Engineer, involved in radio over fiber systems. In 2005, he joined the University of Zaragoza, where he is an Associated Professor with the Electronics Engineering and Communications Department. His research interests include the area of microwave photonics, mobile antenna systems, passive microwave devices, and power amplifiers.

MARIA ANGELES LOSADA received the Ph.D. degree in physics from the Universidad Complutense de Madrid, Madrid, Spain, in 1990. From 1991 to 1994, she was a Postdoctoral Researcher with the McGill Vision Research Laboratories, McGill University, Montreal, QC, Canada, and, afterward with the Institute for Research in Optics of the Scientific Research Council of Spain, Madrid. In 1997, she joined the Department of Electronic Engineering and Communications, University of Zaragoza, Zaragoza, Spain, where she has a tenured position. In 2002, she became a member of the Photonic Technologies Group, Aragon Institute for Engineering Research, University of Zaragoza. Her research interests are centered in optical communications and in particular the application of plastic optical fibers as the media for optical networks in short-haul environments.

DWIGHT RICHARDS (Member, IEEE) received the B.E. and M.E. degrees in electrical engineering from the City College of New York, New York, NY, USA, in 1993 and 1996, respectively, and the Ph.D. degree from the Graduate School, City University of New York, in 1999. He is currently an Associate Professor with the Department of Engineering and Environmental Science, The College of Staten Island (CSI), City University of New York, Staten Island, NY. Prior to joining CSI, he was the Leader of the Optical System Simulation Framework Development Group with RSoft Design Group, where he spent five years. Before that, he was a member of the Technical Staff with Telcordia Technologies, Red Bank, NJ, USA, where he spent five years. His current research interests include optical communication networks with an emphasis on simulation methodologies, avionics communication systems, and photonic integrated circuits.

ABDUL AZIZ (Member, IEEE) received the bachelor's degree in computer science from the COMSATS Institute of Information Technology, Lahore, Pakistan, in 2013, and the master's degree in computer science from the National University of Computer and Emerging Sciences, Karachi, Pakistan, in 2018. He is currently pursuing the Ph.D. degree in computer science with the Advanced Information Systems Laboratory of the Aragon Institute of Engineering Research, University of Zaragoza. His research interests include open data, information retrieval, and open data portal domains.