Computer Networks 173 (2020) 107209

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Narrowband Internet of Things: A Comprehensive Study

Eshita Rastogi[a], Navrati Saxena[b,*], Abhishek Roy[c], Dong Ryeol Shin[b]

[a] College of Information and Communication Engineering, Sungkyunkwan University, Suwon, South Korea
[b] College of Software, Sungkyunkwan University, Suwon, South Korea
[c] Wireless Standard Team, MediaTek USA Inc., USA

ARTICLE INFO

Keywords:
NB-IoT
LPWA
LTE
5G-NR
3GPP

ABSTRACT

Over the last decade, the number of Low-Power Wireless Access (LPWA) devices has increased remarkably. It has become crucial to introduce several LPWA technologies to share the burden of catering to the demands of these devices. Narrowband Internet of Things (NB-IoT) is one such new cellular LPWA technology which has been standardized by 3rd Generation Partnership Project (3GPP) in June, 2016. It was developed with the aim to support low-complexity and low-power devices serving areas of poor radio coverage. In this survey, we review NB-IoT technology in detail. NB-IoT's architecture is derived from that of Long Term Evolution (LTE) cellular technology, which is another 3GPP technology. We first discuss the architectural changes made to the design of LTE to derive the design of NB-IoT, including changes in physical layer and layer-2 architecture. Next, we describe the various features introduced for NB-IoT in 3GPP Rel-13 and follow it up to describe the enhancements made in subsequent 3GPP releases until 3GPP Rel-16. Then, we review, in depth, the research work done on various aspects of NB-IoT. We follow it up with a discussion on the combination of NB-IoT with other interesting cellular technologies like Device-to-Device communication (D2D), Non-Orthogonal Multiple Access (NOMA), social IoT, and 5th Generation New Radio (5G NR). We also look into a wide variety of real-world applications of NB-IoT. Finally, we point out a few open issues of NB-IoT and identify possible future research directions.

1. Introduction

Internet of Things (IoT) has undergone a drastic change in the last few years. The number of IoT devices are increasing at a phenomenal rate and several new IoT applications related to vehicles, logistics, power grid, agriculture, metering, etc. have sprung up. A number of Low Power Wide Area (LPWA) technologies have come into picture to cater this high demand of data. These technologies support a number of features like deep coverage, low power consumption, large number of users, and low device complexity. The standardization of LPWA technologies is carried out by different standard development organizations like IEEE, 3GPP, etc. The LPWA technologies can be cellular or non-cellular wireless technologies. The cellular technologies include Machine Type Communication (MTC), enhanced Machine Type Communication (eMTC), Narrowband Internet of Things (NB-IoT), etc. whereas non-cellular technologies include Long Range (LoRa), ZigBee, Bluetooth, Z-Wave, etc [1]. In this review, we provide an exhaustive review of NB-IoT technology.

NB-IoT is a LPWA technology which was proposed by 3GPP in September, 2015 [2] and was eventually standardized by 3GPP in June, 2016 [3]. It is continuing to evolve in subsequent 3GPP releases. The advantage of narrowband transmission lies in providing both coverage and capacity extension [4]. The architecture of NB-IoT is extensively derived from legacy LTE. NB-IoT technology is appropriate for users transmitting low, infrequent, and delay-tolerant data. Furthermore, ubiquitous coverage, scalability, and coexistence with LTE network has made the deployment of NB-IoT simpler and faster. Moreover, NB-IoT operates in licensed bands, due to which interference issues associated with this technology are limited [5]. We now describe some of the key objectives of NB-IoT in the following subsection.

1.1. Objectives of NB-IoT

The key objectives of NB-IoT are described in 3GPP standards [6] and are shown in Fig 1.

1. *Deep Coverage*: NB-IoT system aims to provide both indoor and outdoor deep coverage [7]. The coverage of NB-IoT is up to 20 dB more when compared to the legacy LTE network [8]. While conventional LTE supports a Maximum Coupling Loss (MCL) of 144 dB, NB-IoT supports an MCL of 164 dB. According to 3GPP standards, high coverage can be achieved by bandwidth reduction and by increasing the number of data transmission repetitions [9]. Bandwidth reduction improves the Power Spectral Density (PSD) of the user, thereby increasing the coverage. The number of data transmission repeti-

* Corresponding author.
E-mail addresses: eshita@skku.edu (E. Rastogi), navrati@skku.edu (N. Saxena), Abhishek.Roy@mediatek.com (A. Roy), drshin@skku.edu (D.R. Shin).

https://doi.org/10.1016/j.comnet.2020.107209
Received 13 October 2019; Received in revised form 2 February 2020; Accepted 9 March 2020
Available online 10 March 2020
1389-1286/

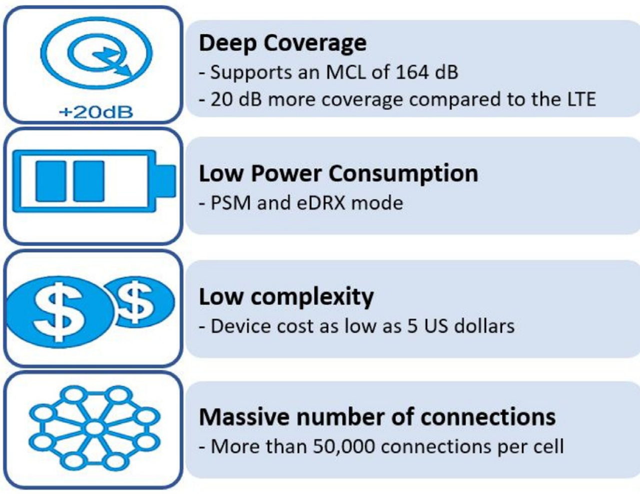

Fig. 1. Objectives of NB-IoT.

tions for increasing the coverage depends on NB-IoT user's Coverage Enhancement (CE) level. Three CE levels, CE-0, CE-1, and CE-2, are defined. A maximum of 2048 repetitions for Downlink (DL) and 128 repetitions for Uplink (UL) are defined [10,11]. However, there are two trade-offs of increasing the coverage. Bandwidth reduction decreases the data rate while a large number of repetitions increases data transmission latency and device's energy consumption [12].

2. *Low Power Consumption*: NB-IoT devices are designed to have more than 10 years of battery life. To ensure a long battery life of NB-IoT devices, 3GPP Rel-12 and Rel-13 have introduced Power Saving Mode (PSM) and enhanced Discontinuous Reception (eDRX) modes, respectively. NB-IoT devices are designed to have more than 10 years of battery life with a battery capacity of 5 Watt-hours, MCL of 164 dB, UL data transmission of 200 bytes per day, and DL response of up to 65 bytes [6]. Both these technologies aim to save the battery of NB-IoT device by putting the device into sleep mode when no data transmission or reception is required [18,19]. PSM provides a large power saving with a maximum sleep duration of 310 h. But due to the long response time to DL data arrival in PSM, it is unsuitable for applications like smart metering and smart grid. Therefore, 3GPP Rel-13 introduced eDRX, which improves DL accessibility. eDRX works in both idle and connected states of the NB-IoT device. In eDRX, maximum sleep cycles of 2.91 h and 10.24 s are supported for idle and connected states, respectively [20].
3. *Low Complexity*: NB-IoT device cost should be kept below 5 US dollars. In order to reduce the device cost, NB-IoT device structure and network layers have been simplified and optimized. Network protocol volume as well as the number of channels, signals, and transceivers are reduced in NB-IoT as compared to the legacy LTE system. There is only one transceiver for both UL and DL transmissions [9]. Since NB-IoT supports only low data rate applications, it does not require high capacity memory, which, in turn, reduces the device cost. NB-IoT devices do not require an IP multi-media system, which also reduces the cost.
4. *Support of Massive Number of Connections*: NB-IoT aims to support more than 50,000 connections per cell [9]. In NB-IoT communication model, users send only low, infrequent, and delay-tolerant data. So, a massive number of devices can be catered simultaneously by a single cell. Also, NB-IoT UL transmission uses a subcarrier-level transmission, which provides a higher utilization of UL resources. NB-IoT supports two numerologies for single-tone transmission: 15 kHz and 3.75 kHz. In 3.75 kHz scheme, a single evolved Node B (eNB) can support simultaneous UL transmission of 48 users. The signalling overhead of NB-IoT is also simplified as compared to legacy LTE. With the decrease in number of signalling messages between eNB and user, the resources can be released in less time duration. This also helps in accommodating more number of users.

1.2. NB-IoT: Motivation and contributions

Exhaustive surveys on IoT and LPWA technologies have found that the number of IoT devices connected to the Internet is growing at an unparalleled rate [1,21]. Amongst all LPWA technologies, the market is drifting towards deploying NB-IoT technology [22]. Since NB-IoT is an open 3GPP standard, it provides deployment flexibility coupled with broader market support. It can easily co-exist with the existing cellular technologies. Thus, being a commercial success, it has attracted numerous companies and large number of researchers round the globe. The existing surveys on NB-IoT are listed in Table 1. To the best of our knowledge, there is no survey that covers all aspects of NB-IoT. This motivates us to perform an exhaustive literature survey on NB-IoT. In this article, we review NB-IoT in detail and provide contemporary information according to the latest 3GPP standards and the research activity in NB-IoT. Also, point out the open issues and future research challenges associated with this technology. The main contributions of this manuscript are enumerated below:

1. We describe the overall architecture of NB-IoT including a clear picture of Evolved Terrestrial Radio Access Network (E-UTRAN) architecture and deployment modes of NB-IoT. Next, we discuss the layer-1 and layer-2 design of NB-IoT. We also highlight the main differences between NB-IoT and legacy LTE.
2. We discuss the progress of NB-IoT in various 3GPP releases in detail. We also include the expected enhancements in NB-IoT in 3GPP Rel-16.
3. We categorize the work done on NB-IoT in different domains and present a detailed summary of the research work done in those domains until now.
4. We describe the co-existence of NB-IoT with several other promising technologies like Device-to-Device communication (D2D), Machine-to-Machine (M2M) communication, Non-Orthogonal Multiple Access (NOMA), social IoT, and 5G.
5. We cover a wide spectrum of interesting of applications of NB-IoT.
6. We discuss the limitations of NB-IoT in detail. We describe open research challenges associated with NB-IoT technology and present future scope of research in this domain.

The architecture of the paper is as follows: Section 2 describes the contribution of industries in making NB-IoT a commercial success. Next, we describe the architecture of NB-IoT in Section 3, which also includes the deployment modes of NB-IoT. In Section 4, we discuss the physical layer architecture of NB-IoT, where the UL and DL physical channels and signals of NB-IoT are described. Subsequently, we describe Layer-2 design of NB-IoT. Next, in Section 5, we discuss the evolution of NB-IoT where we extensively discuss the enhancements made in NB-IoT until 3GPP-Rel 15 and also briefly discuss the on-going research work in 3GPP-Rel 16. In Section 6, we discuss the research work done in different domains of NB-IoT. Next, we describe the performance of NB-IoT with other technologies like D2D, M2M, NOMA, 5G, etc. in Section 7 of the review. We describe the major applications of NB-IoT in Section 8 and point out open research issues in Section 9. Finally, Section 10 concludes our survey. Table 2 provides the list of abbreviations used in the manuscript.

2. Industrial work on NB-IoT

NB-IoT is a commercial success because it has attracted various organizations and industries which have collaborated to deploy NB-IoT in different aspects [65]. Over the years, there has been a massive surge in the number of smart devices, industries, building utili-

Table 1
Surveys on NB-IoT.

Existing Surveys	Industrial Work	Architecture			Evolution				Updated Research	Applications	Open Issues
		Core	L 1	L 2	R13	R14	R15	R16			
Xu et al. [9]				*	*					*	*
Chen et al. [13]			*		*					*	*
Elsaadany et al. [14]			*		*						*
Wang et al. [15]			*	*							*
Ayoub et al. [16]		*	*		*					*	
Mwakwata et al. [17]		*	*	*	*	*	*	*		*	
Our Survey	*	*	*	*	*	*	*	*	*	*	*

Table 2
List of abbreviations.

Symbols	Meaning	Symbols	Meaning
3GPP	Third Generation Partnership project	5G	5th generation
AM	Acknowledged Mode	CDMA	Code Division Multiple Access
CE	Coverage Enhancement	CP	Cyclic Prefix
CRS	Cell-specific Reference Signal	DCI	Downlink Control Information
eCID	Enhanced Cell ID	eDRX	Enhanced Discontinuous Reception
EDT	Early Data Transmission	eMBB	Enhanced Mobile Broadband
eNB	eNodeB	EPS	Evolved Packet System
EUTRAN	Evolved Universal Terrestrial Radio Access Network	FDD	Frequency Division Duplexing
HARQ	Hybrid Automatic Repeat Request	LTE	Long Term Evolution
MAC	Medium Access Control	MBMS	Multimedia Broadcast Multicast Service
MCL	Maximum Coupling Loss	MIB-NB	Narrowband Master Information Block
MIMO	Multiple Input Multiple Output	MME	Mobility Management Entity
mMTC	Massive Machine Type Communication	NB-IoT	Narrow Band Internet of Things
NB-MIB	Narrowband Master Information Block	NCCE	Narrowband Control Channel Element
DMRS	Demodulation Reference Signal	NOMA	Non-Orthogonal Multiple Access
NPBCH	Narrowband Physical Broadcast Channel	NPDCCH	Narrowband Downlink Common Channel
NPDSCH	Narrowband Physical Downlink Shared Channel	NPRACH	Narrowband Physical Random Access Channel
NPRS	Narrowband Positioning Reference Signal	NPSS	Narrowband Primary Synchronization Signal
NPUSCH	Narrowband Physical Uplink Shared Channel	NSSS	Narrowband Secondary Synchronization Signal
OFDMA	Orthogonal Frequency Division Multiple Access	OTDOA	Observed Time Difference of Arrival
PCI	Physical Cell ID	PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol	PDU	Protocol Data Unit
PO	Paging Occasion	PRB	Physical Resource Block
P-RNTI	Paging-Radio Network Temporary Identifier	PSD	Power Spectral Density
PSM	Power Saving Mode	QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying	RA	Random Access
RAR	Random Access Response	RAT	Radio Access Technology
RLC	Radio Link Control	RSTD	Reference Signal Time Difference
RU	Resource Unit	SCEF	Service Capability Exposure Function
SCFDMA	Single Carrier Frequency Division Multiple Access	SC-PTM	Single Cell Point to Multipoint
SFBC	Space Frequency Block Coding	SNR	Signal to Noise Ratio
TBS	Transport Block Size	TDD	Time Division Duplexing
TDoA	Time Difference of Arrival	TTI	Transmission Time Interval
UCI	Uplink Control Information	UM	Unacknowledged mode
UpPTS	Uplink Pilot Time Slot	URLLC	Ultra-Reliable Low-Latency Communication

ties, etc., all requiring connectivity. According to the Ericsson mobility report, the number of cellular IoT connections will grow from 1 billion to 4.5 billion by 2024 with NB-IoT and CAT-M1 devices comprising 45% of the total number of connections [66]. The major markets of these devices include both consumer-oriented and industrial applications such as logistics, personal wearables, smart metering, smart agriculture, and security services. Key industry players operating in the market include Qualcomm, MediaTek, Intel, Ericsson, and Huawei [67]. They are working on developing new NB-IoT modules and deploying NB-IoT network to improve the coverage and increase the scope of commercial applications where the technology is applied. Also, there are a large number of operators like AT&T, Vodafone, China Mobile, etc. around the globe providing commercial NB-IoT networks as listed in [68]. Table 3 summarizes the industrial work on NB-IoT.

2.1. MediaTek

MediaTek is one of the key players driving the formulation and implementation of NB-IoT [25]. It has introduced two NB-IoT - enabled System-on-Chip (SoC) devices: MT2625 [23] and MT2621 [24]. MT2625 is a 3GPP Rel-14 compatible SoC and is suitable for numerous applications like smart homes, smart beacons, etc. It is expected that the devices using MT625 will consume ultra-low power and be cost effective [23]. MT2621 is a dual-mode IoT SoC that is capable of both NB-IoT (3GPP Rel-14) and GSM/GPRS connectivity. This module supports extended coverage and is ideal for long battery life, ensuring long-term installation. It is capable of enabling applications like smart trackers, IoT security, and other industrial applications [24].

2.2. Qualcomm Technologies

Qualcomm is also working actively towards the deployment of NB-IoT in industrial, residential, and enterprise ecosystems[26]. It has designed a flexible MDM9206 LTE modem to provide reliable and optimized cellular connectivity for IoT products that need low bandwidth and several years of battery life [27]. MDM9206 supports PSM and eDRX for power management [28]. Further details of the product can be found in [28].

Table 3
Industrial work on NB-IoT.

Organization	Related work	Key findings
MediaTek	[23–25]	• Introduced two 3GPP Rel-14-capable NB-IoT devices: MT2625, MT2621 • Supported applications: smart homes, smart beacons, smart trackers, wearables, industrial and household applications
Qualcomm	[26–28]	• Introduced MDM9206 NB-IoT modem which supports PSM & eDRX • Supported applications: smart metering, smart city, object tracking, healthcare, smart parking, sensors
Intel	[29]	• Introduced two NB-IoT devices: XMM 7115, XMM 7315 • Supported applications: smart metering, sensors
Ericsson	[30–33]	• Collaborating with several companies (AstraZeneca, Telstra, DISH, MediaTek, Qualcomm) to expand NB-IoT ecosystem • Supports both radio access & core network devices for NB-IoT • Supported applications: healthcare, real-time surveillance, smart lockers, safety watches
Huawei	[34–37]	• Launched end-to-end NB-IoT solution including smart devices, radio and core network, & cloud-based management platform • Also introduced NB-IoT chips • Supported applications: asset tracking, logistics, pet tracking, smart metering, smoke trackers, smart agriculture
Samsung	[38–41]	• Introduced 3GPP Rel-14 - capable Exynos's i S111 which supports several NB-IoT features such as PSM, eDRX, and OTDOA • Introduced smart tags for reporting location information • Supported applications: smart metering, smart factories, location tracking, smart wearables
Korea Telecom	[42–45]	• Introduced NB-IoT-based LPG metering system & safety jackets • Supported applications: underground parking, hiking trail monitoring, smart metering, smart waste management
LG U+	[46,47]	• Launched NFV-based dedicated core network equipment for NB-IoT • Supported applications: smart cities, industrial IoT, smart metering, location tracking
Vodafone	[48–52]	• Launched NB-IoT-based smart water metering system in U.K. • Plans to use NB-IoT for smart agriculture & connecting farms in New Zealand • Supported applications: sensor networks, smart cities, smart metering, location tracking, smart agriculture
AT&T	[53–55]	• Launched nation-wide NB-IoT service in U.S. & Mexico • Plans to provide world-wide access to NB-IoT network to its customers by signing roaming deals with other companies • Supported applications: smart sensors, smart agriculture, smoke detectors, door locks, industrial monitors
China Mobile	[56–58]	• Launched NB-IoT service in major cities of China • Collaborating with DT Mobile to develop NB-IoT - based smart parking system • Supported applications: smart parking, smart metering, water quality monitoring
Miscellaneous	[59–64]	• Altair, Quectel, and Riot Micro introduced 3GPP Rel-13 - compliant NB-IoT chip-sets • Sequans introduced 3GPP Rel-14 & 15 - compliant Monarch N chip-set • Supported applications: smart metering, asset tracking, smart wearables, smart cities, vehicle telemetries

2.3. Intel

Intel is an important NB-IoT chip-set vendor in the IoT world. It has come up with micro-controllers and SoCs with NB-IoT capabilities: Intel XMM 7115 and Intel XMM 7315 [29]. Intel XMM 7115 modem is designed to support industrial devices and application based on NB-IoT. It can be integrated with sensors, smart meters, and other low-power applications [29]. Intel XMM 7315 supports both LTE-M and NB-IoT technologies. The speed of the modem ranges from 200 kbps (NB-IoT) to 1 Mbps (LTE-M) [29].

2.4. Ericsson

Ericsson has partnered with Telstra to successfully deploy and test NB-IoT data connections up to 100 km from a base-station in Telstras commercial network [32]. It has ecosystem and is planning to launch smart chips that can be used in smart lockers, health bands, children's safety watches etc[33]. Ericsson provides a radio access and core network for DISH's NB-IoT network. Both the companies together validated NB-IoT data transmission for a connection range of 100 km from the base station in USA [31].

2.5. Huawei

Huawei is also working towards the commercialization of NB-IoT. Huawei has launched 3GPP Rel-14 - based NB-IoT solution which solution is expected to increase coverage, data rate (seven-fold), and cell capacity (two-fold), making it suitable for applications like asset tracking, logistics, and pet tracking [34]. It has also commercialized an end-to-end NB-IoT solution which includes smart devices, eNodeB, IoT packet core, and cloud-based IoT connection management platform [35]. It has also shipped NB-IoT chips that support easy integration and low power consumption [36]. NB-IoT is considered one of the promising technologies for use cases like smart metering, smoke trackers, smart agriculture, etc. and is both commercially and technically ready for deployment in some parts of China [37].

2.6. Samsung

Samsung is also contributing towards building NB-IoT networks. Samsung and Korea Telecom (KT) are preparing for commercialization of NB-IoT in order to enter the fast-developing IoT market [38]. Furthermore, along with KT, Samsung announced a pilot service for the near-future in Seoul, South Korea to extend diverse service models and coverage. The diverse service models will include applications like utility metering, smart factories, cargo tracking, and location tracking of children and goods [39]. It also launched a Samsung-connect tag which offers smart location notification based on the NB-IoT network [40]. Samsung also announced NB-IoT solution Exynos's i S111 which offers extremely wide coverage, low-power consumption, accurate location feedback, and strong security, optimized for todays real-time tracking applications such as safety wearables or smart meters [41]. Exynos's i

S111 complies with 3GPP Rel-14 and can operate in standalone, in-band, and guard-band deployments. It supports PSM and eDRX for power management and Observed Time Difference of Arrival (OTDOA) method for positioning.

2.7. Korea Telecom (KT)

KT considers NB-IoT as a promising technology for its IoT business due to advantages like roaming and interoperability, better QoS guarantee, enhanced security, and cost-effectiveness. KT plans to deploy NB-IoT for several use-cases such as smart metering, smart waste management, disaster prevention, anti-theft, asset management, location tracking, smart factory, etc[44]. KT, along with Dalim Special Vehicle, launched an NB-IoT - based remote LPG metering system which will track the tank level in the LP gas tank and efficiently manage fuel delivery [42]. KT teamed-up with Kolon Industry to make IoT safety jackets featuring an NB-IoT communication module made by Intel. This will help a person in distress to be rescued by sending signals and alerts in case of an emergency. These modules are cheap, consume low power, and continue to work even in areas with weak signal strength [43]. KT has used Nokia's NB-IoT base station and dedicated core network equipment for diverse applications like underground parking garages and monitoring of remote hiking trails [45].

2.8. LG U+

LG U+ also aims to expand the NB-IoT ecosystem by catering to applications like public utilities, industrial IoT, and smart city applications [46]. It launched the deployment of Network Function Virtualization (NFV)-based, NB-IoT - dedicated core network equipment called cellular IoT - Serving Gateway Node (C-SGN). Along with KT, it has plans to begin the deployment of NB-IoT in South Korea by offering services like smart metering, location tracking, smart cities, etc. [47].

2.9. Vodafone

Vodafone is working actively towards building a world-wide NB-IoT ecosystem and believes that NB-IoT can be the best solution for low-cost, wide-area deployment [48]. The large variety of applications offered by Vodafone to potential customers include sensor networks, smart city applications like smart lighting and smart bins, tracking, etc [49]. Vodafone had launched NB-IoT technology in New Zealand, where it aims to provide better agriculture facilities and to connect farms in future [50]. Furthermore, Vodafone's NB-IoT network is used to monitor water meters and fix water leakage in United Kingdom [51]. Vodafone is also planning to launch NB-IoT service in India with an aim to provide smart metering facilities in the major cities of India [52].

2.10. AT&T

AT&T is a major telecommunication vendor and has launched a nation-wide NB-IoT network in the U.S. and Mexico [53]. AT&T is also working towards developing NB-IoT - enabled multi-modules that can connect devices to NB-IoT network [54]. AT&T and Vodafone together are planning to enable a roaming deal between U.S. and some countries in Europe so that the customers can access their NB-IoT network across these countries [55].

2.11. China Mobile

China Mobile has deployed NB-IoT networks in major cities of China since it believes that NB-IoT will provide extensive coverage, will support a large number of connections, and will consume less power [56]. It is now planning to launch fully commercial NB-IoT service which is expected to support a wide range of applications including smart parking, smart metering, and water quality measurement [57]. China Mobile, together with DT Mobile, is working on a smart parking service system with an aim to provide better parking facilities [58].

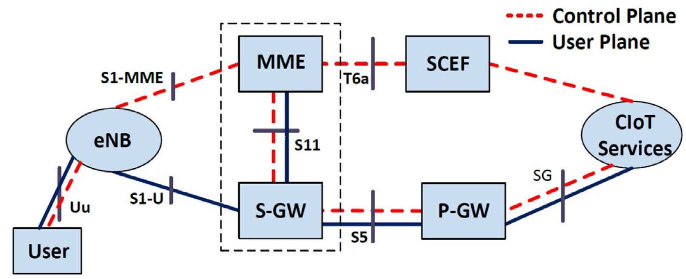

Fig. 2. Overall architecture of NB-IoT.

2.12. Miscellaneous

Other NB-IoT chip vendors are also contributing towards building a strong NB-IoT ecosystem [59]. Altair has launched ALT1250, which is a 3GPP Rel-13 CAT-M1 and NB-IoT - enabled chip-set suitable for ultra-low power consumption devices [60]. Quectel has launched the BC95 module which supports NB-IoT and is compliant with 3GPP Rel-13 [61]. It is well suited for LPWA applications. Similarly, Riot Micro has developed RM1000 compatible with 3GPP Rel-13 for both LTE-M and NB-IoT [62]. Sequans has also launched Monarch N which is an advanced NB-IoT - based module compliant with 3GPP Rel-14 and 15 [63]. It is suitable for low data rate applications like asset tracking, wearables, etc. NTT DoCoMo and Sequans have worked together on NB-IoT devices and applications on NTT Docomo's network where Sequans Monarch LTE Platform (LTE-M/NB-IoT version) and Monarch N (NB-IoT-only version) chip solution will be used [64].

3. NB-IoT architecture

NB-IoT architecture is derived from the architecture of legacy LTE. However, LTE's architecture has been modified to fulfill the requirements of NB-IoT. In particular, this section explains the overall architecture of NB-IoT, as described in 3GPP Rel-13.

Fig. 2 shows the control plane (CP) and the user plane interfaces for NB-IoT radio access network in red and blue colors, respectively [3,69]. The NB-IoT eNB is connected to the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the NB-IoT user by S1-MME, S1-U, and Uu interfaces, respectively. The S-GW is connected to the Packet Data Network Gateway (P-GW) by S5 interface and similarly, the P-GW is connected to the service point by SG interface. The MME is connected to the Service Capability Exposure Function (SCEF) by T6a interface [70]. The SCEF is a new node added to the NB-IoT architecture. It delivers non-IP data over the CP and provides interface for the network services including authorization, authentication, access network capability, and discovery. This node is not present in the conventional LTE architecture.

For NB-IoT user, data can be transferred over the CP. The user data is first transferred from the eNB to the MME, then to the S-GW, and finally, to the P-GW and the service point. For NB-IoT, S11-U interface is newly added between the MME and the S-GW and is not present in conventional LTE architecture. For data transfer over the user plane, the user data is first transferred from the eNB to the S-GW and then, to the P-GW and the service point [3,69].

In both UL and DL, NB-IoT supports Frequency Division Duplexing (FDD) mode with channel and full carrier bandwidths of 200 kHz and 180 kHz, respectively [3]. It supports single antenna in the user and two to four antennas in the eNB. NB-IoT defines three CE levels in a cell: CE-0, CE-1, and CE-2, having a MCL of 144 dB, 154 dB, and 164 dB, respectively. Fig. 3 shows the coverage levels of NB-IoT.

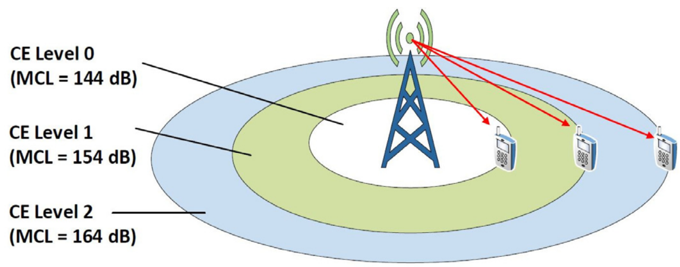

Fig. 3. Coverage levels of NB-IoT.

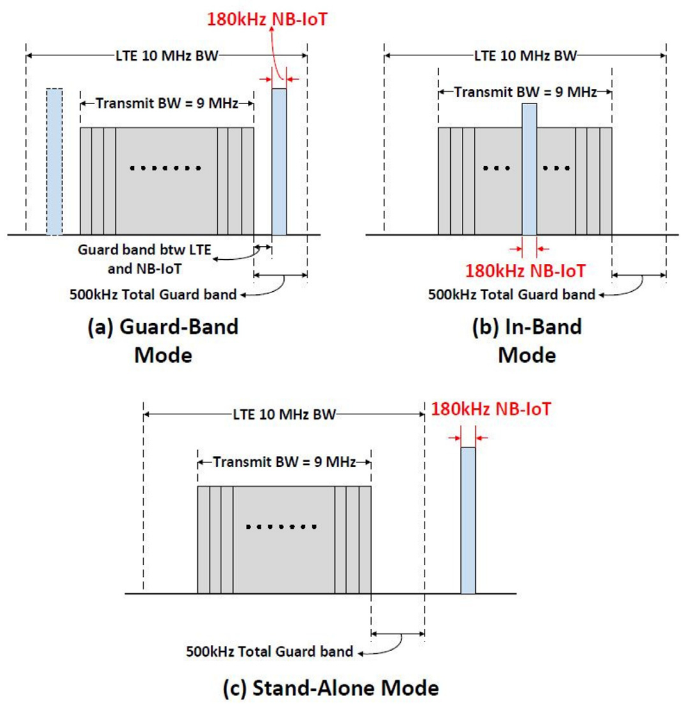

Fig. 4. Deployment modes of NB-IoT.

NB-IoT supports three deployment modes: (i) In-band mode (ii) Guard-band mode and (iii) Stand-alone mode [6]. The three deployment modes of NB-IoT are shown in Fig. 4.

1. *In-band Mode*: In this mode, a single Physical Resource Block (PRB) within legacy LTE bandwidth is reserved for both UL and DL. However, NB-IoT is not allowed to use the resources reserved for LTE Physical Downlink Control Channel (PDCCH) and LTE Cell Specific Reference Signal (CRS). When there is no NB-IoT traffic, the PRB allocated for NB-IoT may be used by the LTE network. NB-IoT traffic and legacy LTE traffic are multiplexed by the eNB's scheduler. To make the system fully flexible, in-band operation supports two modes, considering cell ID and number of antennas: (i) Same Physical Cell ID (PCI) mode, where these parameters of LTE and NB-IoT are identical and (ii) Different PCI mode, where these parameters may be different for LTE and NB-IoT [71].
2. *Guard-band Mode*: In this mode, an LTE carrier can support an NB-IoT carrier in either of its two guard-bands [72]. This mode is only supported for LTE carriers using a bandwidth of 5 MHz or more. The impact of interference between LTE and NB-IoT on UL of NB-IoT is very small [72]. No PRB of the LTE network is reserved for NB-IoT.
3. *Stand-alone Mode*: In this mode, NB-IoT is used in a new frequency carrier. For example, the NB-IoT carrier may replace an existing GSM carrier. The resource usages of stand-alone and guard-band modes are similar. Similar to the guard-band operation, it does not affect the existing LTE network.

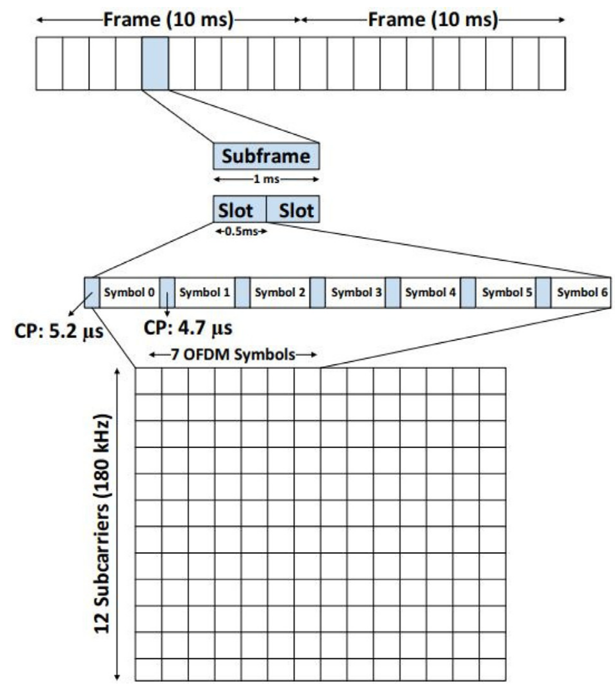

Fig. 5. Frame structure of downlink.

4. Layer-1 and Layer-2 architecture of NB-IoT

In this part of the survey, we describe the layer-1 (physical layer) and the layer-2 architecture of NB-IoT, as described in 3GPP Rel-13. In NB-IoT, up to some extent, the design of physical channels is based on legacy LTE. We first provide an overview of both UL and DL physical channels and signals. Then, we describe the changes in layer-2 architecture of NB-IoT as compared to that of LTE.

4.1. Downlink physical channels and signals

Fig 5 describes the frame structure of DL NB-IoT. Similar to legacy LTE, NB-IoT uses Orthogonal Frequency Division Multiple Access (OFDMA) with a subcarrier spacing of 15 kHz. A subframe with a span of 1 ms, with two slots of 0.5 ms each, is used in NB-IoT. Each slot has 7 OFDMA symbols. The number of channels and signals are reduced in NB-IoT as compared to LTE. The physical channels and signals of NB-IoT are as follows: (i) Narrowband Physical Broadcast Channel (NPBCH), (ii) Narrowband Physical Downlink Control Channel (NPDCCH), (iii) Narrowband Physical Downlink Shared Channel (NPDSCH), (iv) Narrowband Primary Synchronization Signal (NPSS), (v) Narrowband Secondary Synchronization Signal (NSSS), (vi) Narrowband Reference Signal (NRS).

Since the Hybrid Automatic Repeat Request (HARQ) feedback information for UL traffic channel is delivered with New Data Indicator (NDI) in Downlink Control Information (DCI), therefore Physical HARQ Indicator Channel (PHICH) is not defined in NB-IoT.

4.1.1. NPBCH

NPBCH is responsible for carrying Narrowband Master Information Block (MIB-NB) and is always transmitted in the first subframe (subframe #0) of any radio frame [3]. MIB-NB is divided into 8 blocks and each block is transmitted 8 times. So, there are 64 transmissions per MIB-NB and the total time taken is 640 ms. NPBCH uses QPSK modulation and contains 34 bits, where 18 bits carry system information and 16 bits carry Cyclic Redundancy Check (CRC) [73]. It supports two antenna ports.

4.1.2. NPDCCH

NPDCCH carries scheduling information for both UL and DL [3]. It uses QPSK modulation and is transmitted using Narrowband Control Channel Elements (NCCEs). Each NCCE corresponds to six consecutive subcarriers: 0 - 5 for NCCE 0 and 6 - 11 for NCCE 1. NPDCCH supports two aggregation levels: (i) Format 0, having 1 NCCE and (ii) Format 1, having 2 NCCEs. Depending on the CE level, the number of repetitions supported for NPDCCH are {1, 2, 4, 8, 16, 128, 256, 512, 1024, 2048} [74].

NPDCCH search space is a specific region which the user monitors for DL data or UL scheduling grant. The period of search space is defined by the product of the starting subframe of NPDCCH and the maximum number of repetitions. There are two types of search spaces: user-specific search space, which is used to schedule user data transmission and common search space, which is used for paging, random access response (RAR), and message-3 and 4 transmissions [71]. Three DCI formats are defined for NPDCCH: (i) Format N0 is used for UL scheduling and carrier information about resource allocation, HARQ, modulation and coding etc., (ii) Format N1 is used for DL scheduling and RA initiated by NPDCCH, and (iii) Format N2 is used for paging and direct indication. The maximum payload size of N0, N1, and N2 formats are 23 bits, 23 bits, and 14 bits, respectively.

4.1.3. NPDSCH

NPDSCH is used for DL data transmission. It carries user data, system information, paging message, and Random Access Response (RAR) message [3]. It uses a single HARQ process with adaptive and asynchronous re-transmission. It uses QPSK modulation with a maximum Transport Block Size (TBS) of 680 bits. In order to reduce implementation complexity, NPDSCH uses Tail-Biting Convolution Coding (TBCC). For error detection, NPDSCH supports 24-bit CRC [73]. NPDSCH supports two DL transmission schemes: (i) single antenna port (Port 0), which does not support Multiple Input Multiple Output (MIMO) and (ii) two antenna ports (Ports 0 and Port 1), which supports SFBC [75]. The transmission duration of NPDSCH is calculated by the product of the number of assigned subframes and the number of repetitions [71,74].

4.1.4. Synchronization signals

NB-IoT synchronization signals are used for timing and frequency synchronization and for Physical Cell Identity (PCID) detection. NPSS is transmitted in subframe #5 of every frame [3]. It uses OFDMA symbol-3 to symbol-13 and subcarrier-0 to subcarrier-10. It is not allocated in LTE PDCCH region. Frequency domain length-11 Zadoff-Chu (ZC) is used to generate NPSS sequence [74].

NPSS provides synchronization information of the subframe but does not provide any information of PCID. NSSS is transmitted in subframe #9 of every frame after every 20 ms [3]. It uses OFDMA symbol-3 to symbol-13 and subcarrier-0 to subcarrier-11. Frequency domain length-131 ZC is used to generate NSSS sequence. NSSS indicates one of the PCIDs from 504 unique PCIDs [74].

4.1.5. NRS

NRS is inserted for the purpose of channel estimation by the user [3]. NRS may be transmitted using single antenna port (Port 0) or two antenna ports (Port 0 and Port 1). When two antenna ports are used, NRS transmission uses transmit diversity with Space Frequency Block Coding (SFBC). The NRS sequence is derived from the PCID and is cyclically shifted by PCID modulo 6 in frequency domain. In the same-PCI mode in-band deployment, the number of antenna ports for transmitting reference signal in LTE and NB-IoT are the same [74]. So, LTE CRS can also be used by NB-IoT user for channel estimation. The power offset between NRS and LTE CRS is provided in SIB-1.

4.2. Uplink physical channels and signals

The UL physical channels and signal are as follows: (i) Narrowband Physical Uplink Shared Channel (NPUSCH), (ii) Narrowband Physical Random Access Channel (NPRACH), (iii) Demodulation Reference Signal (DMRS)

4.2.1. NPUSCH

NPUSCH is used to carry UL data and supports enhanced coverage, long battery life, and improved capacity [75]. NPUSCH has two formats: (i) Format 1, used to carry UL-SCH and (ii) Format 2, used to carry Uplink Control Information (UCI) [3]. Unlike conventional LTE's Physical Uplink Control Channel (PUCCH), NB-IoT does not use a separate channel to carry UCI. Both the formats are based on Single-Carrier FDMA (SC-FDMA). NPUSCH uses a single HARQ process with two Redundancy Versions (RV) and a maximum TBS of 1000 bits. It supports the following number of repetitions: {1, 2, 4, 8, 16, 32, 64, 128} [71].

Fig. 6 describes the frame structure of NPUSCH. NPUSCH Format 1 supports both single-tone transmission and multi-tone transmission [3]. In single-tone transmission, the two numerologies with 15 kHz and 3.75 kHz subcarrier spacing use resource unit time duration of 8 ms and 32 ms, respectively. In multi-tone transmission, subcarriers can be grouped into sets of 3, 6, or 12 subcarriers. Multi-tone transmission uses resource unit time duration of 4 ms, 2 ms and 1 ms for groupings of 3

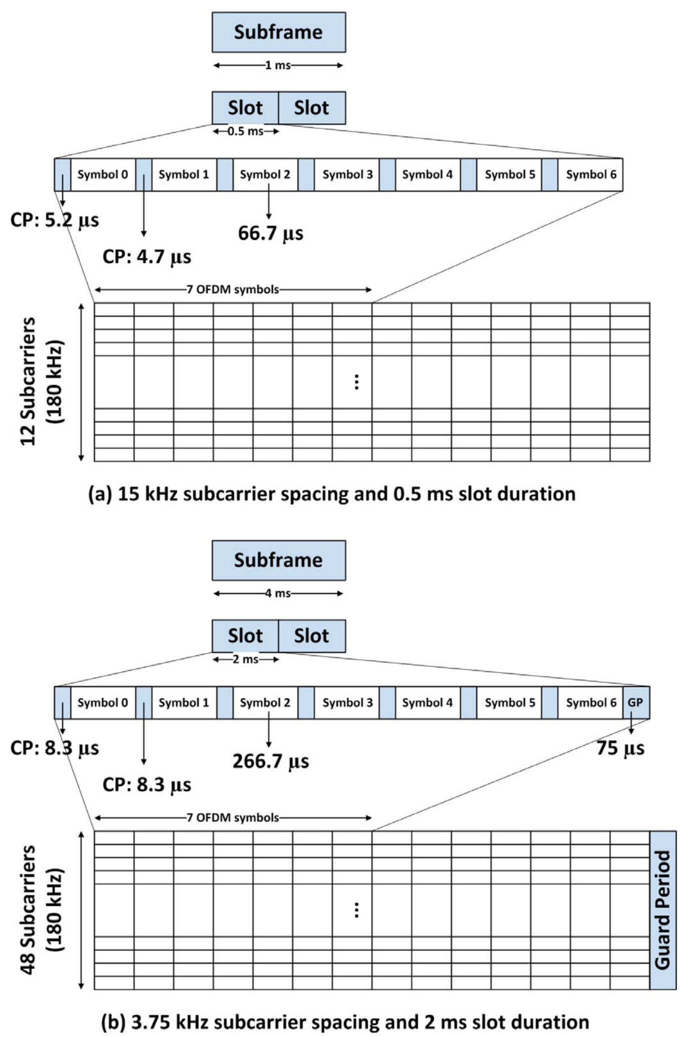

Fig. 6. Frame structure of NPUSCH (a) 15 kHz subcarrier spacing and 0.5 ms slot duration (b) 3.75 kHz subcarrier spacing and 2 ms slot duration.

subcarriers, 6 subcarriers, and 12 subcarriers, respectively. For error detection, NPUSCH Format 1 uses turbo-coding and a 24-bit CRC. Single-tone transmission uses $\pi/2$-BPSK and $\pi/4$-QPSK modulation schemes while multi-tone transmission uses QPSK modulation scheme [73].

NPUSCH Format 2 supports only single-tone transmission with 15 kHz and 3.75 kHz subcarrier spacing and resource unit time duration 2 ms and 8 ms, respectively [3]. It uses $\pi/2$-BPSK and $\pi/4$-QPSK modulation schemes. For error detection, it uses block-coding but no CRC [73].

4.2.2. NPRACH

In NB-IoT, Random Access (RA) procedure is used to establish an initial link between the user and eNB. NPRACH is used for preamble transmission from user to eNB in RA procedure [76]. The DL received signal power is measured by the user to estimate its CE level. NPRACH resources for each CE level are different. The eNB can identify the CE level of the user from the used NPRACH resources.

In frequency domain, NPRACH uses a subcarrier spacing of 3.75 kHz and occupies either 12, 24, 36, or 48 contiguous subcarriers [3,77]. In time domain, there are two preamble formats which differ in CP length: (i) Format 0 (ii) Format 1. Each NPRACH preamble has 4 symbol groups where each group consists of a Cyclic Prefix (CP) and 5 symbols. The 5 symbols are 1.333 ms long. The CP can be 66.7 μs (Format 0) or 266.7 μs (Format 1) long depending on the cell radius, leading to symbol group durations of 1.4 ms or 1.6 ms, respectively [74]. Preamble transmission may be repeated 1, 2, 4, 8, 16, 32, 64, or 128 times. NPRACH periodicity can be configured from 40 ms to 2.56 s.

NB-IoT supports multi-level frequency hopping [74]. The frequency hopping algorithm ensures that there are as many collision-free preambles as there are number of NPRACH subcarriers. There is no sequence for cell ID in the NPRACH signal [74]. So, its performance is hampered by interference from other cells. To mitigate the inter-cell interference, NPRACH frequency regions in different cells are separated by applying different carrier offsets.

4.2.3. DMRS

It is a user-specific reference signal used to estimate the channel response in UL and is transmitted along with NPUSCH. For NPUSCH Format-1 with single-tone transmission, DMRS is transmitted in the fourth SC-FDMA symbol of the slot for 15 kHz subcarrier spacing and in the fifth SC-FDMA symbol of the slot for 3.75 kHz subcarrier spacing [3]. The sequence length is 16 and multiple reference signals are created using different base sequences and a common Gold sequence. For NPUSCH Format-1 with multi-tone transmission, DMRS is transmitted in the fourth SC-FDMA symbol of the slot [3]. The sequence length is the same as the number of assigned subcarriers and multiple reference signals are created using different base sequences and different cyclic shifts of the same sequence. For NPUSCH Format-1, DMRS sequence-group hopping in frequency domain can also be enabled [74].

For NPUSCH Format-2 with single-tone transmission, DMRS is transmitted in the third, fourth, and fifth SC-FDMA symbols of the slot for 15 kHz subcarrier spacing and in the first, second, and third SC-FDMA symbols of the slot for 3.75 kHz subcarrier spacing [3]. Multiple reference signals are created using different base sequences, a common Gold sequence, and different Orthogonal Cover Codes.

4.3. Layer 2 architecture

The complexity of NB-IoT devices is low as compared to legacy LTE devices. So, there are several design features which are changed in NB-IoT. This subsection describes the layer-2 architecture of NB-IoT as per 3GPP Rel-13. The enhancements made in layer-2 architecture in further 3GPP releases are described in Section 5 of the review.

In NB-IoT, Medium Access Control (MAC) is optimized and supports flexible scheduling, reduced power consumption, and reduced overhead on the protocol stack processing flow [69]. Since NB-IoT devices are designed for low throughput, unlike legacy LTE, NB-IoT only supports single HARQ process. This helps in reducing the complexity of NB-IoT device. NB-IoT does not support non-contention-based RA and channel quality indicator reporting [9]. Furthermore, in order to decrease the complexity, it supports open loop power control in UL and does not support closed loop power control [78]. In open loop power control, eNB does not send power control command to the user. The user can determine UL transmission power according to Modulation and Coding Scheme (MCS) and Resource Units (RUs). Exclusion of closed loop power control algorithm reduces a lot of device complexity [78,79].

In Radio Link Control (RLC) layer, NB-IoT only supports Transparent Mode (TM) and Acknowledged Mode (AM). NB-IoT does not support voice service in Rel-13 and so, Unacknowledged Mode (UM) has been removed [80]. Packet Data Convergence Protocol (PDCP) layer is not used when control plane optimization (see Section- 5) is used and when access stratum (AS) security is not activated in user plane optimization (see Section- 5) [3]. PDCP status report function is not used in NB-IoT [81]. Since handover is not supported in NB-IoT, therefore, re-transmission of PDCP SDUs at handover is removed in NB-IoT. For the same reason, mobility management is removed from the RRC layer [3].

Finally, we can say that although layer-1 architecture of NB-IoT in 3GPP Rel-13 has been derived from LTE, several changes have been made to the architecture in order to support NB-IoT objectives such as low device complexity and low power consumption. These changes include reduction in number of physical channels and signals and simplified design of the remaining channels and signals (for example, smaller number of Tx/Rx antennas, lower TBS, simpler modulation and coding schemes, etc.). Similarly, layer-2 architecture of NB-IoT has also been simplified w.r.t. LTE. Major changes are in NB-IoT's MAC layer which supports only 1 HARQ process, only contention-based RA, only open-loop power control, and no CSI report. 3GPP Rel-13 layer-1 and layer-2 architectures of NB-IoT and LTE are compared in Table 4.

5. Evolution of NB-IoT

Prior to NB-IoT, 3GPP had standardized two LPWA technologies, eMTC and User Category-0 (Cat-0), in 3GPP Rel-10 and 3GPP Rel-12, respectively, to serve the growing number of IoT devices. However, these technologies were not enough to satisfy the demands of billions of IoT devices. Considering this scenario, Huawei and Qualcomm proposed Narrow-Band-Cellular IoT (NB-CIoT). Later,Nokia, Ericsson and AT&T proposed Narrow-Band LTE (NB-LTE) which could co-exist with legacy LTE. Similarly, Ericsson also proposed Extended Coverage Global System1 for Mobile Communication (EC-GSM) which could be used in the existing GSM network with some software upgrades. Finally, in 2015, 3GPP Rel-13 officially included NB-IoT and EC-GSM in the standardization process [82]. Authors in [83] describe NB-IoT deployment history and the research activities in this field.

3GPP Rel-13 introduced NB-IoT and described its architecture. To encounter a few shortcomings in the initial release, the subsequent 3GPP releases added new features and modified some of the existing features of NB-IoT. This section covers the features introduced in 3GPP Rel-13 and all the enhancements introduced in later 3GPP releases.

5.1. Release 13 (March, 2016)

NB-IoT solution focuses on delay insensitive, low data rate devices. In this regard, 3GPP Rel-13 introduces optimization defined for NB-IoT: Control Plane (CP) Optimization and User Plane (UP) Optimization [3]. The signalling overhead, especially over the radio interface, is minimized using these optimization procedures [19].

5.1.1. Control Plane (CP) optimization

Fig. 7 shows the data flow in the network using CP Optimization [3]. Unlike conventional LTE, there is no Access Security (AS) setup and data

Table 4
Layer 1 and Layer 2 comparison of NB-IoT and LTE (3GPP Rel-13).

Parameters	NB-IoT	LTE
Access Medium	UL: SC-FDMA, DL: OFDMA	UL: SC-FDMA, DL: OFDMA
Carrier Spacing	UL: QPSK, pi/4 QPSK, pi/2 BPSK, DL: QPSK	UL: QPSK, 16 QAM, 64 QAM, DL: QPSK, 16 QAM, 64 QAM, 256 QAM
Modulation	UL: 15 kHz, 3.75 kHz, DL: 15 kHz	UL: 15 kHz, DL: 15 kHz
Max Payload	UL: 1000 bits, DL: 680 bits	UL: 195816 bits, DL: 391656 bits
	(i) Frequency resource allocation for NPUSCH can be done in units of less than 1 PRB. (ii) NPUSCH is transmitted over a single layer only. (iii) NPUSCH Format 1 and Format 2 are coded using Turbo code and repetition code, respectively.	(i) Frequency resource allocation for PUSCH can be done in units of 1 PRB only. (ii) PUSCH can be transmitted over multiple layers with spatial multiplexing. (iii) PUSCH is coded using Turbo code.
	NPRACH is transmitted over 1 PRB using single-tone frequency hopping with 3.75 kHz subcarrier spacing	PRACH is transmitted over 6 PRBs using multi-tone transmission with no frequency hopping and 1.25 kHz subcarrier spacing
	DMRS sequences are generated by OCC to base sequences generated from Gold sequences	DMRS sequences are generated by applying cyclic shifts and OCC to base sequences which are cyclic extensions of Zadoff-Chu sequences.
Channels & Signals	Through NPBCH, MIB is transmitted over a 640ms TTI	Through PBCH, MIB is transmitted over a 40ms TTI
	NPDCCH is transmitted over 1 PRB in a subframe but is spread over several subframes	PDCCH is transmitted over multiple PRBs in a subframe
	NPDSCH is coded using tail-biting convolution code and is transmitted using 1 RV	PDSCH is coded using Turbo code and can be transmitted using 4 RV
	(i) NPSS is transmitted with a periodicity of 10ms over 1 PRB. (ii) NPSS does not carry information about PCID.	(i) PSS is transmitted with a periodicity of 5ms over 6 PRBs. (ii) PSS carries some information about PCID
	NSSS is transmitted with a periodicity of 20ms over 1 PRB	SSS is transmitted with a periodicity of 10ms over 6 PRBs
	NRS sequence is derived from PCID and is transmitted on 1 or 2 antenna ports over 1 PRB	CRS sequence is derived from PCID and is transmitted on 1 - 4 antenna ports over all PRBs
	Not supported in NB-IoT	PUCCH, SRS, PMCH, PCFICH, PHICH, MBSFN RS, PRS, CSI-RS
MAC	• 1 HARQ process • No CSI report • Only contention-based RA • Only open loop power control • In RRC_CONNECTED state, maximum DRX cycle length of 9.216 s is possible • In RRC_IDLE state, when eDRX is used, maximum DRX cycle length of 10.24s in a PTW of 2.91 h is possible. After eDRX, user enters PSM state which ends when T3412 timer expires (max. value of 413.3 days).	• 8 HARQ processes • CSI report supported • Contention-based, non-contention-based RA • Open loop, closed loop power control • In RRC_CONNECTED state, maximum DRX cycle length of 10.24 s (based on eDRX) is possible • In RRC_IDLE state, maximum DRX cycle length of 2.56 s is possible
RLC	Acknowledged Mode, Transparent Mode only	Acknowledged, Unacknowledged, Transparent Modes
PDCP	• PDCP is not used with CP optimization and when AS security is not activated in UP optimization • PDCP status report function is not supported • Since handover is not supported PDCP PDU re-transmission is not supported	• PDCP is always used • PDCP status report function is supported • PDCP PDU re-transmission due to handover is supported

Note: PUCCH: Physical Uplink Control Channel, SRS: Sounding Reference Signal, PMCH: Physical Multicast Channel, PCFICH: Physical Control Format Indicator Channel, PHICH: Physical HARQ Indicator Channel, MBSFN RS: Multimedia Broadcast Multicast Service Single Frequency Network Reference Signal, PRS: Positioning Reference Signals, CSI-RS: Channel State Information Reference Signal, OCC: Orthogonal Cover Codes, RV: Redundancy Version

radio bearer setup. The data packets, encapsulated as NAS Protocol Data Units (PDU), are sent from the eNB to the MME over the S1 interface. The MME transfers them to S-GW using the newly-introduced S11-U interface. Fig. 8 shows the data transfer procedure between the eNB and the user for mobile-originated data [3]. The user starts the data transmission procedure by transmitting a randomly-selected preamble. After detecting the RA response send by the eNB, the user transmits the Radio Resource Control (RRC) Connection Request message, and receives the RRC Connection Setup Message. Until now, NB-IoT RA procedure is the same as that for conventional LTE. In conventional LTE, RRC Connection Setup Complete message includes only control information. However, the NB-IoT user can also include UL data (encapsulated as NAS PDU) in this message.

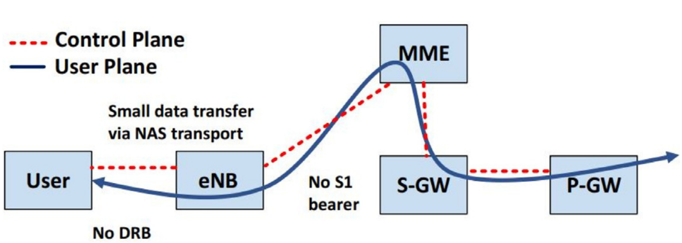

Fig. 7. Control Plane (CP) optimization [3].

Later, if the NB-IoT user has more UL data to send to the eNB, it can encapsulate the data as NAS PDU and send it using RRC UL Information Transfer message. Similarly, the eNB can also encapsulate DL data as NAS PDU and send it to the user through RRC DL Information Transfer message. Similarly, the eNB can also send more DL data to the user

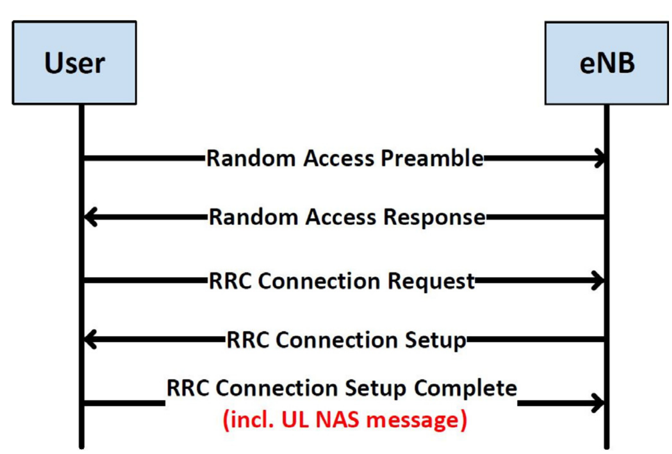

Fig. 8. Signalling of data flow in CP optimization [3].

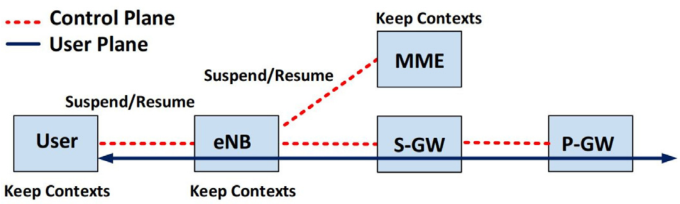

Fig. 9. User Plane (UP) optimization [3].

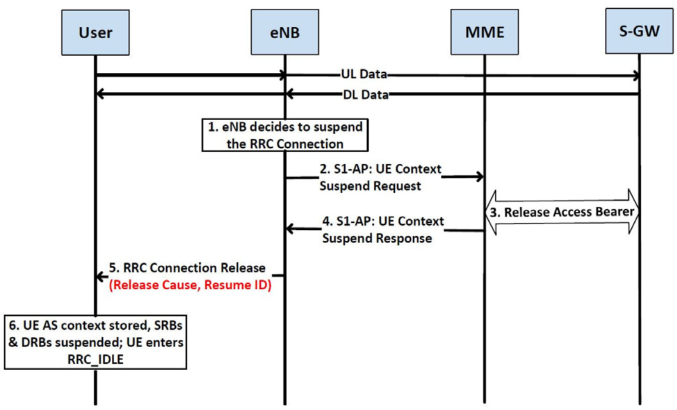

Fig. 10. RRC Connection Suspend Procedure [3].

through RRC DL Information Transfer message. For mobile-terminated data, a similar procedure is followed. The only differences are that paging is required to inform the user about pending DL data and that eNB starts sending the data in RRC Connection Setup message itself. CP optimization is suitable for transmission of small data. However, if the size of the data to be transferred increases beyond a limit, the user can trigger the establishment of the data radio bearer between the eNB and the S-GW. In this case, the S11-U bearer between MME and S-GW is released [20].

5.1.2. User Plane (UP) optimization

When the size of data to be transferred is more than a threshold, NB-IoT data can be transferred using UP optimization procedure. Here, the user can ask the network to setup a data radio bearer. Then, the data is transferred in the same way as in conventional LTE. The support of UP optimization is optional for NB-IoT user [20]. Fig 9 shows the data flow in UP optimization procedure [3]. The user establishes an RRC connection with the network which configures the data radio bearers and the AS security context. After initial data transmission is over, the user releases the RRC connection and move to the RRC_IDLE state using RRC Suspend procedure as shown in Fig. 10 [3]. The user releases all the bearers but saves the AS security context. The eNB informs the MME to suspend all the bearers for the user and provides a Resume ID to the user which can be used later in RRC Connection Resume procedure shown in Fig. 11 [3].

When the user wants to re-establish RRC connection, it does not have to establish a new connection. Instead, it can resume the old connection by sending the RRC Connection Request Resume message, including the Resume ID. The eNB resumes the connection, AS security is re-established, and the user enters RRC_CONNECTED state. Subsequently, data exchange between the user and the eNB is possible. Since the connection is resumed, the latency of transition from RRC_IDLE to RRC_CONNEC TED state is reduced. As UP optimization procedure utilizes the user plane for data transmission, it is suitable for both small and large data transmission.

The user can also resume the RRC connection in a new eNB, different from the one which suspended the RRC connection. When the new eNB receives RRC Connection Resume Reqst message, it fetches the user context, including Resume ID, from the old eNB. After that, the same procedure as described above for RRC Connection Resume procedure is followed by the new eNB and the user.

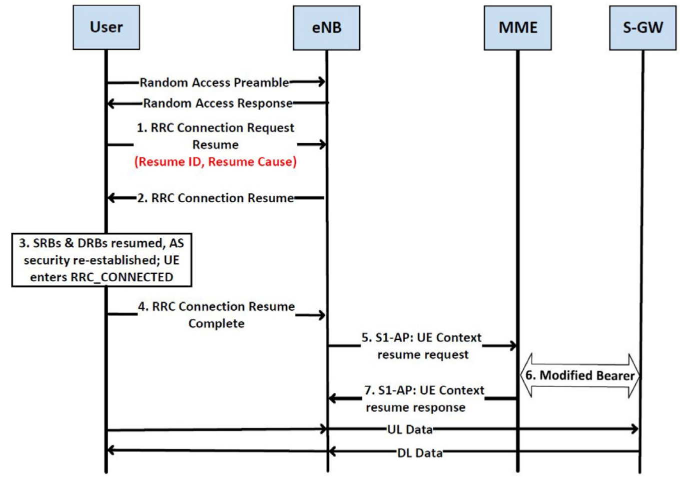

Fig. 11. RRC Connection Resume Procedure [3].

5.1.3. Power saving techniques

NB-IoT is designed for devices having a long battery life of 10 years or more. In RRC_CONNECTED state, an NB-IoT user can save power through DRX feature. When there is no data to send or receive, the user enters DRX sleep state and wakes up periodically at a defined Paging Occasion (PO) to check whether there is P-RNTI on the PDSCH or not. In case P-RNTI is present, the user starts to receive data from PDSCH. Then, it goes to sleep state again and waits until the arrival of next PO. Since the maximum DRX cycle length is 9.216s, the beginning of two POs can be separated by a maximum of only 9.216s. In RRC_IDLE state, there are two mechanisms for saving power in NB-IoT : PSM (3GPP Rel-12) and eDRX (3GPP Rel-13) [84]. The network can configure the NB-IoT user with two timers: Tracking Area Update (TAU) timer (T3412) and active timer (T3324) as shown in Fig. 12. When the user enters RRC_IDLE state, both the timers start running at the same time. In RRC_IDLE state, while T3324 is running, the user receives paging at regular POs. When eDRX is not used, two POs can be separated by a maximum of 10.24s. When eDRX is used, a Paging Time Window (PTW) is defined and the user receives paging at regular POs within the PTW. Two PTWs can be separated by up to 2.91 h. After T3324 expires, the NB-IoT user enters PSM and remains in PSM until T3412 expires. T3412 can be set to a maximum duration of 413.3 days, configurable in units of 310 h. The time spent by the user in PSM is given by the difference of these two timers (i.e., T3412 - T3324). In PSM, the device is registered but is not connected to the network as it turns off the radio and is inaccessible by the network [85]. The power saving in RRC_IDLE state is more when compared to RRC_CONNECTED state.

PSM allows a large amount of power-saving for the device but due to its large response time for mobile-terminated traffic, it is only suitable for applications having relaxed real-time requirements. To overcome the problem of large response time, we can configure a longer value of T3324 and a shorter value of T3412, leading to more frequent paging opportunities for the device. However, without eDRX, this configuration increases device power consumption due to very frequent POs while T3324 is running. Since eDRX enables the configuration of a longer value for T3324 with infrequent paging, for some applications, it provides a fair trade-off between device accessibility and power consumption.

5.2. Release 14 (June, 2017)

This subsection describes the enhancements made in NB-IoT in 3GPP Rel-14.

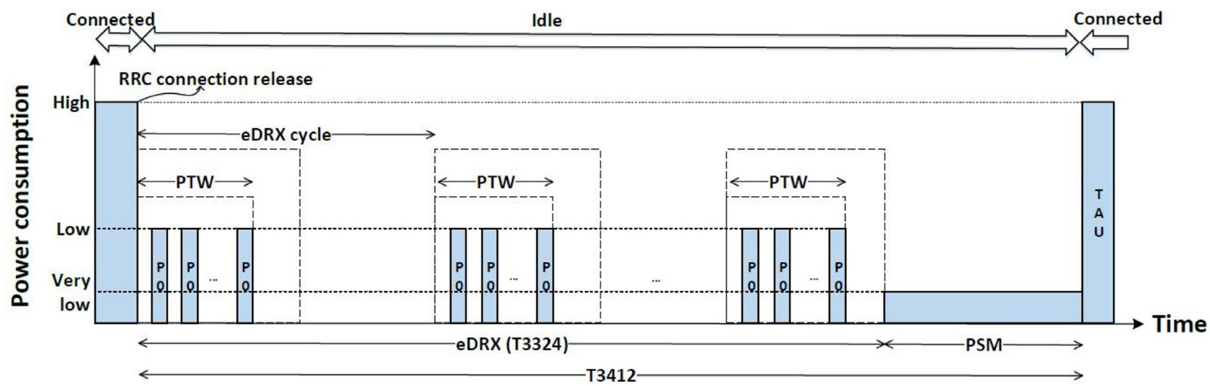

Fig. 12. Power-saving mechanism in RRC_IDLE state in NB-IoT (eDRX and PSM).

5.2.1. Category-NB2 (CAT-NB2)

Until 3GPP Rel-13, NB-IoT supported only NB1 user category (CAT-NB1), which is meant for low data rates. It supports UL and DL peak data rates of 65 kbps and 25 kbps, respectively. Later, it was felt that some NB-IoT use-cases need to support diverse traffic scenarios with slightly higher data rates. Therefore, 3GPP Rel-14 introduces a new user category known as CAT-NB2 [86]. Unlike CAT-NB1, which supports a maximum Transport Block Size (TBS) of 1000 bits and 680 bits for UL and DL, respectively, CAT-NB2 supports a maximum TBS of 2536 bits for both UL and DL. Apart from increasing the TBS, CAT-NB2 optionally supports two HARQ processes. In CAT-NB1, the throughput is limited because of two reasons: NPDCCH scheduling delay and number of repetitions. The second HARQ process increases the throughput gain by decreasing the overhead due to NPDCCH scheduling gap. This enhancement increases the peak data rate of NPUSCH from 106 kbps to 158.5 kbps and of NPDSCH from 79 kbps to and 127 kbps [87]. However, it does not affect the number of repetitions and hence its gain is limited to throughput in good radio conditions only [87].

5.2.2. Positioning

There are several use cases like wearable devices, machinery control, safety monitoring, smart parking, smart vehicles, etc. where the knowledge of users position is essential. Until Rel-13, NB-IoT supported only a basic positioning method based on the knowledge of the ID of the cell the user was connected to. By knowing the cell ID, the user's location could be matched to the cell's coverage area. In 3GPP Rel-14, this method was enhanced to allow to the NB-IoT user to measure and report eNB's Rx-Tx time difference, Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ). This enhanced positioning method is called enhanced cell ID (eCID) method [88].

3GPP Rel-14 also introduced another positioning method, Observed Time Difference of Arrival (OTDOA), for NB-IoT users [88,89]. For this purpose, a new Narrowband Positioning Reference Signal (NPRS) was introduced. NPRS is sent to enhance positioning measurement at the receiver. Similar to legacy LTE's PRS, NPRS also offers orthogonality in three domains: time domain (including muting for listening to weak cells), frequency domain (reuse factor of 6), and code domain (different cells can use different sequences). In OTDOA, the Times of Arrival (ToA) of NPRS from a reference eNB and the neighbor eNBs are estimated. By measuring the time difference, the user's Reference Signal Time Difference (RSTD) can be estimated. Each RSTD measurement restricts the user's position to a hyperbola. The point of intersection of several such hyperbolas gives the user's location [90].

Authors in [91] use OTDOA for tracking NB-IoT device. This OTDOA report can be sent to the user either periodically or on an on-demand basis. Here, the authors investigate the possibility of optimizing the number of OTDOA reports using on-demand reporting method based on Signal to Noise Ratio (SNR). Authors in [92] propose a Space Alternating Generalized Expectation Maximization (SAGE) based method to ToA. This proposed method outperforms a traditional ToA estimator which uses SNR or power threshold-based estimation. Research work in [93] proposes an iterative Expectation Maximization-Based Successive Interference Cancellation (EM-SIC) detector to jointly consider the fading channel, frequency offset, and ToA of the first arrival path. The positioning performance depends on the location of the serving eNB, the location of the surrounding eNBs with respect to the user, and the accuracy of the positioning observation [94]. In [94], authors propose a tractable model of NB-IoT system to investigate the impact of participating eNB on NB-IoT positioning performance in random scenario. Parameters like device location, cell coverage and channel condition are considered to study the impact of the number of participating eNBs. However, the work did not consider the impact of directional antennas and power control, and performance of different networks like multi-tiered heterogeneous network. Rsado et al. [95] discuss the impact of frequency hopping in NB-IoT positioning. Downlink Time Difference of Arrival (TDoA) is used to determine the positioning performance. This scheme give the position accuracy of up to 50 m. However, the proposed mechanism did not consider the receiver architecture and channel constraints. Authors in [96] propose a CSI amplitude fingerprinting based localization algorithm in NB-IoT to reduce the positioning error. However, the proposed algorithm does not consider diverse NB-IoT devices and interference among the NB-IoT devices.

5.2.3. Multicast

Multicast can be understood as group communication. Here, a single transmission is used to address a group of users. It is useful in situations where an eNB needs to address several NB-IoT users at once. Legacy LTE's Multimedia Broadcast and Multicast Service (MBMS) scheme is not suitable for NB-IoT. Its high energy consumption and inefficient resource utilization make it unsuitable for NB-IoT. This motivated 3GPP to introduce multicast support through Single-Cell Point to Multipoint (SC-PTM) communication in 3GPP Rel-14 [97,98]. SC-PTM is extended to support multi-cast DL transmission for NB-IoT. In SC-PTM, there are two logical channels: (i) Single Cell Multicast Traffic Channel (SC-MTCH) for carrying data traffic and (ii) Single Cell Multicast Control Channel (SC-MCCH) for carrying periodic control information. These channels are mapped to NPDSCH and are scheduled by NPDCCH. SC-MCCH scheduling information is broadcast using a new System Information Broadcast message (SIB20-NB). SC-MTCH and SC-MCCH use RLC Unacknowledged Mode (UM) which is also added in 3GPP Rel-14. In order to provide better resource utilization and energy consumption, research work in [99] proposes an on-demand (whenever there is a relevant service) resource utilization model. Unlike subscription-based model, it does not require periodic service announcement and MBMS notification procedure. In this paper, the authors propose a novel mechanism for grouping, paging, and delivering content which efficiently supports multicast in NB-IoT.

5.2.4. Multi-carrier enhancement

The number of use-cases for NB-IoT has been continuously growing with time. According to 3GPP TR 45.820, NB-IoT in 3GPP Rel-13 targeted 60,000 devices per square kilometer while NB-IoT in 3GPP Rel-14 targeted 6 million devices per square kilometer [6]. To support so many devices, 3GPP Rel-13 already includes multi-carrier support in NB-IoT where a user can be configured with an anchor carrier as well as a non-anchor carrier. An anchor carrier can support up to 16 non-anchor carriers. However, in 3GPP Rel-13, non-anchor carrier is restricted to offloading data traffic only and does not support operations like paging and RA. This inability to support RRC_IDLE state operations results in capacity bottleneck. This motivated 3GPP to enable both paging and RA procedure on non-anchor carriers in 3GPP Rel-14. This enhancement is expected to increase the capacity of NB-IoT system by causing a major reduction in overhead (approximately 21% for in-band mode and 30% for guard-band and standalone modes) [87].

5.2.5. Low power user

In 3GPP Rel-13, the maximum allowed UL power for NB-IoT users was 20 dBm. In 3GPP Rel-14, a class of users with low power has been introduced in which the maximum UL power is restricted to 14 dBm [100]. Lower UL transmit power enables smaller batteries, low device power consumption, and even lower device cost. However, the decrease in the output power is compensated by the increase in transmission time so that the energy transmitted per bit is maintained [101]. This also helps to maintain the coverage of the low-power users. However, it leads to an increase in UL resource utilization and DL control signalling. In order to deal with this negative impact, 3GPP agreed that the MCL of low-power user can be relaxed as compared to Rel-13 [87].

5.2.6. Release assistance indication

Rel-14 also supports a Release Assistance Indication (RAI) message [89]. NB-IoT is designed for the users that have infrequent and small amount of data to transmit and receive. Once the data transmission is complete, RAI is sent by the user to the eNB indicating that the user does not have any data for transmission. After receiving the message, the eNB releases the RRC connection and the user saves power by returning to the idle state [87].

5.3. Release 15 (Sept,2018)

This subsection describes the enhancements made in NB-IoT in 3GPP Rel-15.

5.3.1. Early data transmission

To prolong the battery life-time of NB-IoT users, it is essential to optimize the power consumption of the NB-IoT device. Early Data Transmission (EDT), standardized in 3GPP Rel-15, aims to improve the battery life of the user and reduce message latency by transmitting small data packets during RA procedure [102,103]. A RA procedure typically includes four steps: (i) RA preamble transmission (Msg-1), (ii) RA response (Msg-2), (iii) Scheduled message (Msg-3), and (iv) Contention resolution (Msg-4). In EDT, the UL and DL data is transmitted in Msg-3 and Msg-4 of RA procedure, respectively. It will reduce the total transmission and reception time of the user as well as the signaling overhead. The maximum TBS that can be utilized for Msg-3 in EDT is broadcasted by the network. The procedure can be triggered using some specific resources only, which are broadcast in SIB22-NB and SIB23-NB. If the data to be transmitted is greater than the threshold broadcast by eNB in SIB22-NB, EDT is not used.

Fig. 13 shows EDT procedure for UP Optimization [102]. Similar to conventional procedure, the user first transmits RA preamble to the eNB. If the user wants to use EDT, then it transmits the preamble using one of the RA resources reserved by the eNB for EDT. After receiving RA response, the user sends RRC Connection Resume Request message. In UP EDT, the user will prepare itself to be ready for data transmission by using the stored AS security context. The user resumes all the radio bearers and once the AS security context is re-established, the eNB can send UL data to S-GW via MME. If S-GW has any DL data to be sent to the user, it is piggy-backed in the NAS PDU in the RRC Connection Release message as shown in Fig. 13. This keeps the user in RRC_IDLE state. If the eNB wants to bring the user to RRC_CONNECTED state, then it transmits RRC Connection Resume message instead of RRC Connection Release message.

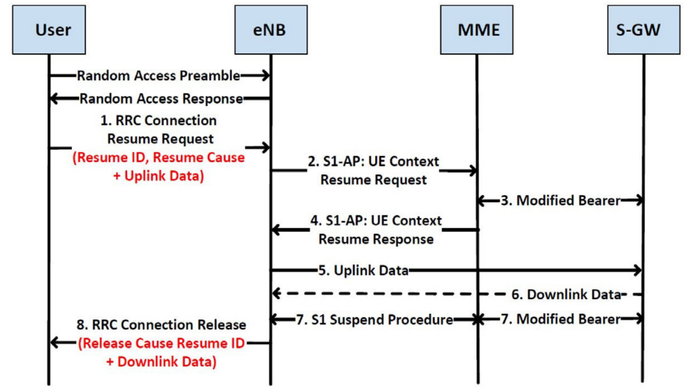

Fig. 13. EDT for user plane optimization [102].

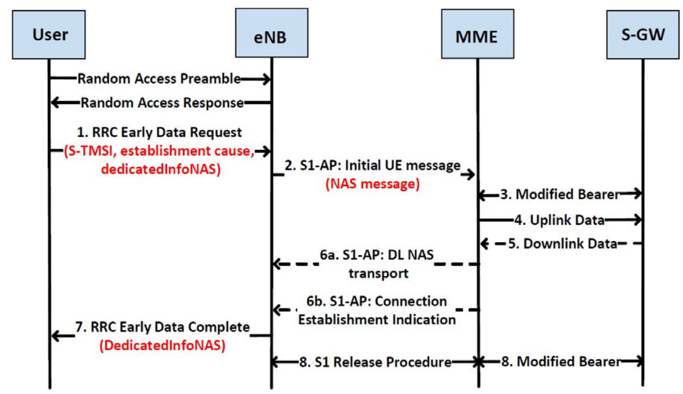

Fig. 14. EDT for control plane optimization [102].

Fig. 14 shows EDT procedure for CP Optimization [102]. In CP EDT, the UL and DL data is transmitted before Msg-5, so that the user remains in RRC_IDLE state. Similar to conventional procedure, the user first transmits RA preamble to the eNB. After receiving RA response, the user sends RRC Early Data Request message. This message is newly included in 3GPP Rel-15 and allows the user to encapsulate the UL data as a NAS PDU within the message. Now, the eNB sends NAS message to MME which transfers the NAS message to S-GW. If S-GW has any DL data to be sent to the user, it is piggy-backed in the NAS PDU in the RRC Early Data Complete message, as shown in Fig. 14. When this message is received by the user, it releases further connection with the eNB and remains in RRC_IDLE state.

5.3.2. Time division duplexing

Until 3GPP Rel-14, only FDD mode was supported in NB-IoT, which restricted the optimum utilization of available spectrum. From 3GPP Rel-15, NB-IoT also supports Time Division Duplex (TDD) mode for both UL and DL [102]. However, there are a few differences between TDD in conventional LTE and in NB-IoT. In conventional LTE, several DL/UL subframe configurations are used to define which subframes will be DL,

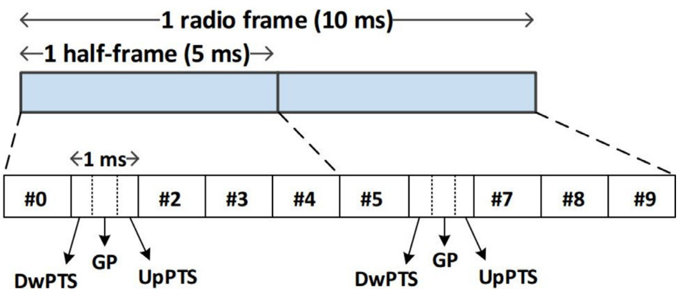

Fig. 15. TDD frame structure (5 ms Switch time period) [102].

UL, and special subframes within a frame. For special subframes also, there are several configurations which define which OFDM symbols will be Downlink Pilot Time Slot (DwPTS) symbols, Uplink Pilot Time Slot (UpPTS) symbols, and guard symbols. In TDD for NB-IoT, use of DL/UL subframe configuration #0 and #6 is not allowed. Use of all special subframe configurations is allowed but the use of UpPTS symbols for UL transmission is prohibited. Fig. 15 shows TDD frame structure for 5 ms switch point periodicity. Master information transmission happens in different subframes in FDD and TDD carriers for NB-IoT. So, a new Master Information Block for TDD (MIB-TDD-NB) has been defined for use on TDD frequencies. The old MIB-NB is used on FDD frequencies only. Two new cyclic prefixes for RA preambles have been defined. Also, only the following combinations of anchor + non-anchor deployment modes can be used for TDD: in-band + in-band, in-band + guard-band, guard-band + in-band, guard-band + guard-band, and stand-alone + stand-alone.

5.3.3. Wake-up signal

3GPP Rel-15 introduced a Wake-Up Signal (WUS) to further reduce the NB-IoT users power consumption [102]. The eNB broadcasts the information related to WUS in System Information [104]. This information is related to the WUS duration, the frequency domain location of WUS, the number of POs with which the WUS is associated, and the time-offset between the WUS and the first PO [104]. If a user is in RRC_IDLE state and supports WUS, then, first, it tries to detect the WUS instead of the paging message in the PO. If the user detects WUS, then it decodes the next few paging messages. Otherwise, it waits for the next WUS occasion. So, the users power consumption is reduced since it has to decode a smaller number of paging messages.

5.3.4. Minor enhancements

Other NB-IoT enhancements in 3GPP Rel-15 [102] are:

1. NB-IoT users are allowed to send Scheduling Requests (SR). SR resources can be assigned or revoked through RRC signalling. SR can be transmitted with or without HARQ ACK/NACK for NPDSCH.
2. Radio Link Control (RLC) Unacknowledged Mode (UM) bearers for NB-IoT users are supported. In 3GPP Rel-14, NB-IoT users could use RLC UM bearers only for SC-PTM transmission.
3. 1.25 kHz sub-carrier spacing for NPRACH with the minimum hopping distance of 1.25 kHz is supported. This enhancement is expected to improve reliability and coverage enhancement.
4. NB-IoT deployment in small-cell is supported. Small-cells include microcell, picocell, and femtocell. Authors in [105] discuss about the various deployment aspects of small-cells in NB-IoT.
5. Transmission of Msg-4 including a MAC PDU containing only user contention resolution identity, without any RRC message, is supported.

5.4. Release 16

In 3GPP, discussions on a number of enhancements for NB-IoT in 3GPP Rel-16 are currently on-going. Some of these proposed enhancements are summarized below [106].

1. To improve DL transmission efficiency, mobile-terminbated EDT and user-group WUS may be supported.
2. When user is in RRC_IDLE state, in order to reduce network access time and improve user power consumption, UL transmission in dedicated pre-configured resources may be allowed if the user has a valid timing advance value.
3. To support Self-Organizing Network (SON) function, an NB-IoT user may optionally report about Cell Global Identity, strongest neighbors, RA performance, radio link failure, etc.
4. Idle-mode inter-Radio Access Technology cell (RAT) selection to and from LTE may be added to enhance user mobility.
5. Issues related to co-existence of NB-IoT with 5G NR may be addressed.
6. Other possible enhancements: Scheduling multiple DL/UL transport blocks with or without DCI, enhancements to multi-carrier operation, connection to 5G core network, etc.

Finally, we conclude that the NB-IoT architecture introduced in 3GPP Rel-13 was designed to support basic NB-IoT objectives of deep coverage, low power consumption, low complexity, and massive number of connected devices. In 3GPP Rel-14, some enhancements to support higher data rate(2 HARQ processes, larger TBS), better device positioning techniques, multicast, lower power consumption in RRC_CONNECTED state (max. output power of 14 dBm), and efficient paging were added to the architecture. In 3GPP Rel-15, NB-IoT was further enhanced to support lower latency (EDT), lower power consumption in RRC_CONNECTED state (WUS), and new deployment options (TDD, small-cell). These enhancements are summarized in Table 5.

6. NB-IoT until now

The wide variety of use-cases are a major guiding force behind the research in NB-IoT. In this section we explore the research work done in the field of NB-IoT until now. We have categorized our work according to various performance parameters in order to give a broad picture of the ongoing research in NB-IoT.

6.1. Deep coverage

A primary objective of NB-IoT technology is to provide deep indoor coverage. NB-IoT aims for 20 dB improvement in coverage compared to LTE network and supports MCL of 164 dB [107]. Authors in [107] consider standalone and inband deployment scenarios for NB-IoT and evaluate its coverage performance comprehensively. However, this work did not take into account inter-cell interference in the network. Similarly, in [108], the authors explain that coverage enhancement can be achieved by repetition of transmitted signal, RU number modification, and bandwidth reduction. However, their analysis is based on an analytic model and does not consider a realistic estimate of NB-IoT channel. They deduce that CE level of the user decides its transmission repetition number. In weak coverage conditions like basements, the coverage can be enhanced by signal repetition as it boosts the quality of received signal. However, [10] shows that channel's estimation quality and coherence time limit the coverage improvement. Analysis in [10] observes that the amount of coverage improvement expected from signal repetition is reduced when the channel coherence time is short.

Authors in [109] focus on the UL coverage enhancement. Authors formulated an optimization problem having latency as an objective function and SNR as a constraint. The three optimization methods called exhaustive search, fsolve, and Lagrangian are evaluated based on accuracy and speed. The Lagrangian method outperforms the others in terms of

Table 5
Summary of NB-IoT features in 3GPP Rel-13, Rel-14, and Rel-15.

Functions	Rel-13 (March, 2016)	Rel-14 (June, 2017)	Rel-15 (Sept, 2018)
User Category	Only CAT-NB-1: • 1 HARQ process • UL max. TBS: 1000 bits • DL max. TBS: 680 bits	CAT-NB-1 and CAT-NB-2 For CAT-NB-2: • Max. 2 HARQ processes • UL and DL max. TBS: 2536 bits	CAT-NB-1 and CAT-NB-2 For CAT-NB-2: • Max. 2 HARQ processes • UL and DL max. TBS: 2536 bits
Positioning Support	CID-based positioning	CID, eCID, and OTDOA-based positioning	CID, eCID, and OTDOA-based positioning
Multicast Support	Not supported	Supported through SC-PTM	Supported through SC-PTM
Max. User Power Output	20 and 23 dBm	14, 20, and 23 dBm	14, 20, and 23 dBm
Multi-carrier Support	Anchor carrier: Data transmission, paging, and RA Non-anchor carrier: Data transmission	Both anchor and non-anchor carriers: Data transmission, paging, and RA	Both anchor and non-anchor carriers: Data transmission, paging, and RA
Early Data Transmission	Not supported	Not supported	Supported
TDD Support	Not supported	Not supported	Supported
Wake-up signal	Not supported	Not supported	Supported
Small-cell Support	Not supported	Not supported	Supported

execution speed and provides the same latency. In [7], authors test NB-IoT in a rural area, compare its coverage with that of legacy LTE, and conclude that, due to high MCL, NB-IoT covers more than 95% of the deep indoor-located devices.

Authors in [110] investigate the deep indoor coverage of various LPWA technologies like NB-IoT, GPRS, Sigfox, and LoRa. In their simulations, the authors evaluated the coverage versus minimum inter-site distance. In spite of experiencing link loss, NB-IoT provides the best coverage which is independent of inter-site distance. Indoor NB-IoT devices experience less than 1% outage while deep indoor devices experience 8% outage. Similarly, in [111], authors describe the coverage performance and the coverage outage probability of NB-IoT in two practical deployment scenarios:(i) Rural network scenario and (ii) deep indoor scenario.

Since the coverage depends on the round trip delay and propagation loss, Ha et al. [76] propose a scheme to expand coverage and call it narrow-band timing advance. Their scheme coverage of NB-IoT cell to more than 35 km. In the proposed scheme, the authors adjust the timing advance such that it expands the service area of NB-IoT. Authors in [112] propose dynamic spectrum access based on reinforcement learning algorithm for enhancing the NB-IoT coverage, decreasing the number of repetitions, thereby reducing the energy consumption. Similarly, in [113], the authors propose to improve the spectral efficiency using an adaptive repetition scheme which uses machine learning. Q-learning algorithm is used to determine the appropriate repetitions for each user. Deng et al. [114] consider hybrid IoTs and in order to guarantee network connectivity, propose a method to fill multi-modal coverage holes.

In summary, we can say that NB-IoT supports deep indoor-located devices because it is designed to support a high MCL. NB-IoT's coverage can be drastically improved by reducing the operational BW and increasing the number of transmitted signal repetitions. However, these methods also reduce the throughput of the user and increase its battery consumption. Some other methods, such as round-trip delay reduction, can also be used to improve coverage.

6.2. Energy management

NB-IoT devices are designed to last for 10 years or more. Therefore, energy efficiency of a device is a critical issue. PSM and eDRX mode were introduced in 3GPP Rel-12 and Rel-13, respectively to ensure a long battery life for the NB-IoT devices. Both these technologies aim to save the battery life by putting the device into sleep mode when no data transmission or reception is required.

Energy consumption is a critical issue as reduction in transmission energy degrades the transmission reliability and Quality of Service (QoS). To address this issue, Liang et al. [115] propose an algorithm to minimize the energy consumed by the device. Their algorithm also maintains ultra-reliable transmission and guarantees QoS. It is divided in two phases: first, the authors optimize the default transmit configuration of the user and then, determine the scheduling order based on scheduling emergency. Research work in [116] proposes a prediction-based energy saving mechanism which predicts the occurrence of UL packet and the delay incurred in processing it. To reduce access delay, it also pre-assigns radio resources. This proposed scheme reduces the energy consumed by up to 34% compared to the conventional schemes and also decreases the number of random accesses.

Chaffi et al. [112] present a machine learning-based algorithm which is based on a trade-off of number of repetitions and energy consumed by the IoT devices. Here, dynamic spectrum access is employed to optimize the number of repetitions and consequently, the energy consumption. Similarly, authors in [117] derive an energy versus latency trade-off based on channel scheduling and repetition. The work proposes an optimized scheduling policy that aims to minimize the latency and maximize the expected battery life. Furthermore, authors in [118] present a semi-Markov model of periodic UL traffic in NB-IoT. The work evaluates a trade-off between energy saving and delay for periodic UL data traffic. Research work in [20] provides an overview of data transportation procedure in NB-IoT and evaluates NB-IoT performance in terms of radio resource usage and energy consumption. Maldonado et al. [119] model CP optimization using Markov chain approach and estimate the average energy consumed and the delay incurred in sending UL messages. They also validate the model using experimental set-up. Their results show that the NB-IoT users can achieve a battery life of 10 years and a latency of 10 s when the traffic profile has an inter-arrival time of 6 s.

In [120], authors consider a cluster-based NB-IoT network and propose a joint resource allocation and power control scheme. The scheme consists of two parts: (i) clustering of NB-IoT devices and (ii) minimizing the energy consumption of the clustered NB-IoT system. The proposed scheme shows significant reduction in energy consumption. Similarly, research work in [121] presentsgrouping-based power-saving DRX scheme for DL traffic to conserve the power of NB-IoT device. The system performance is analyzed using discrete-time semi-Markov model. Authors in [122] investigate traffic offloading through small-cell operating in unlicensed band. They minimize the power consumed by the devices by carrying out traffic scheduling and power allocation jointly. At the same time, they also try to satisfy the security and throughput requirements of the devices.

In [123], authors propose an opportunistic early decoding of DL data based user's channel conditions. This model helps in optimizing the repetition number and reduces the user's energy consumption of the device. The proposed algorithm leads to approximately 45% reduction in the active time of the device at the operating range of 10% block error rate. This significantly improves the battery life of the NB-IoT device. Sultania et al. [124] model energy consumption using Poisson arrival process for UL and DL data transmission. Energy consumption is then analyzed in NS-3 using different timers like PSM timer and eDRX timer.

Similarly, authors in [125] evaluate battery consumption by monitoring the duration of RRC_CONNECTED state. Authors in [126] design a hardware implementation of maximum likelihood NPSS detector which reduces the energy consumed per timing acquisition. However, the computation complexity of the detector is high. Authors in [127] propose teaching learning optimization with an aim to provide better coverage and reduce power consumption.

Hence, we believe that battery consumption of NB-IoT devices can be improved by efficient resource allocation, reducing energy during transmission, and reducing the number of repetitions. Various optimization techniques, including machine learning-based algorithms, have been applied in order to find a balance between reducing battery consumption and maintaining QoS guarantees. In future, study of several other possible trade-offs, like energy consumption vs. resource allocation computational complexity and energy consumption vs. UL transmission delay, can be interesting research directions.

6.3. Random access procedure

This procedure is used to establish a radio link between the eNB and the user. The primary function of RA is to achieve UL synchronization through accurate estimation of ToA, which is also an important parameter for device positioning and UL signal decoding. Lin et al. [128] describe a detailed design of receiver algorithm for NPRACH detection and time-of-arrival estimation which enables the eNB to detect the presence of RA preamble. The proposed scheme has a detection probability of more than 99% with a false alarm probability of less than 0.1%. Its ToA error is within [-3,3] microseconds. However, the work does not provide a detailed performance analysis and does not address the issue of detection threshold estimation. RA preamble detection and ToA estimation is also discussed in [129]. In [130], Hwang et al. investigate the performance of NPRACH from physical layer perspective. The work considers superimposition of NPRACH preambles from multiple users and analyzes the detection probability for both Rayleigh fading channels and additive white Gaussian noise.

In [131], authors derive optimal spectrum sensing parameters which help to achieve the maximum throughput with Narrowband Cognitive Radio IoT (NB-CR-IoT). They consider Slotted-ALOHA NB-CR-IoT where an IoT device, through spectrum sensing, can dynamically access the vacant radio channel. The authors combine cognitive radio and RA strategies to reduce excessive number of collisions during access attempt. Kim et al. [132] propose an enhanced access reservation protocol which utilizes partial preamble transmission. They investigate the trade-off between collision probability and mis-detection and find the optimum resource utilization strategy according to system load. In [133], RA in NB-IoT is modeled using stochastic geometry approach where the authors take into account the number of repeated preamble transmissions and collisions. Success probability in light traffic conditions is improved by the proposed scheme but it fails to work efficiently in heavy traffic conditions. However, research work in both [132] and [133] did not consider re-transmissions at the MAC layer. Authors in [134] investigate the repetition versus re-transmission trade-off in configuring NPRACH. The authors consider both repetition and re-transmission in physical and MAC layer, respectively in order to estimate the performance of RA procedure.

An enhanced RA scheme to reduce delay and power consumption of devices is proposed in [135]. Authors in [136] propose an access class barring mechanism to enhance the access success probability. Here, the users are classified based on the level of tolerance of time delay. Based on the time delay characteristics, lower and higher level users are given longer and shorter back-off time, respectively. The proposed scheme aims to improve the performance of the network by capacity optimization. In [137] and [138], authors estimate the probability and the average delay of network access at a given network load. They also present joint optimization of multiple NB-IoT RA parameters to maximize the access success probability under delay constraints.

ToA estimation is greatly influenced by frequency hopping pattern of RA preamble sequence. In [139], the authors show that an efficient frequency hopping method is essential to enhance the ToA estimation accuracy without adding any extra overhead. However, there is a trade-off between the frequency hopping step size and the ToA estimation accuracy. A large ToA estimation range is supported by using multi-level frequency hopping [128]. In [140], authors propose a probabilistic model which considers packet generation rate, queue length, and re-transmiss ion number to optimize RA procedure and improve throughput.

Thus, we can summarize that RA preamble detection probability analysis is vital for designing and improving NB-IoT's RA procedure. So, various authors have approached this problem by modelling RA procedure in different ways and applying different optimization techniques while considering several parameters like network load, frequency hopping, preamble repetitions and re-transmissions, etc. Similarly, another issue is that RA procedure should support a large number of users while also reducing the access delay in order to decrease the power consumption. So, several researchers have tried to optimize network access delay while considering network load by applying several methods such as access control for delay-tolerant users.

6.4. Massive connections

The support of a large number of low-throughput devices is another primary objective of NB-IoT. To support a large number of devices, the data transmission procedure plays an important role [20]. Authors in [20] describe the CP and UP procedures and evaluate them in terms of cell capacity and energy consumption. In [146], authors propose a scheme which enables the NB-IoT device to transfer small amounts of data in idle state itself without any radio resource connection setup. This scheme increases the maximum number of connected devices by 60% as compared to conventional data transmission schemes. Power-domain UL NOMA is proposed in [148]. Significant increases the number of users connected to NB-IoT system compared to conventional OMA is noticed by the proposed scheme. To increase the number of connected devices, authors in [149] propose a fast OFDM scheme which is expected to double the number of connected devices without compromising the bit error rate and data rate. Also, it provides 50% bandwidth saving when compared to SC-FDMA.

The authors in [153] develop an efficient paging message to increase the paging capacity. The design of the paging message utilizes binary tree to reduce the message size. Similarly, with efficient RA procedure, the success probability of the transmitted RA preamble increases [140]. Moreover, the authors model number of re-transmissions caused by collision using Markov chain model and calculate the throughput of the system by analyzing the number of users served [140].

Thus, we conclude that small data transmission from RRC_IDLE state is an effective way of increasing the number of supported devices. Use of efficient paging and RA procedures can also help in this regard. Several unconventional schemes, such as Fast-OFDM and NOMA, have also been applied to support massive number of NB-IoT devices.

6.5. Resource management

Efficient resource management is crucial for the maximum utilization of radio resources because inappropriate resource allocation leads to the wastage of radio resources. In this subsection, we describe the resource management in DL and UL.

6.5.1. Downlink resource management

Yu et al. [147] discuss DL scheduling problem for NB-IoT network such that each device's data requirement is satisfied. Inappropriate DL scheduling leads to the wastage of time domain radio resources. NPDCCH period corresponds to the time difference between the start of two NPDCCH subframe. The authors proposed NB-IoT scheduling algorithm with an objective of minimizing the required number of NPDCCH periods used to satisfy the requirements of NB-IoT devices. Simulation results show that the proposed algorithm can reduce up to 21.7% of NPDCCH periods compared to the baseline approach. Similarly, authors in [152] explain that appropriate selection of user-specific NPDCCH offset indexes provides high resource utilization by accommodating more number of devices. User-specific and common search space configuration is used to decide the timing of NPDCCH and NPDSCH for different users. The optimized configuration enhances the scheduling efficiency. Authors in [97] consider various use-cases and deployments of NB-IoT and try to understand the channel occupancy for these cases by surveying the related DL and UL performance evaluations. The authors present data transmission and reception procedures and analyze them in terms of latency and resource utilization.

Paging message is initiated by the eNB to establish a connection with the user which periodically monitors the NPDCCH channel for any paging message. An efficient paging scheme is essential to reduce the signalling overhead and increase the capacity of network. Authors in [153] design a paging message using the concept of binary tree. The proposed scheme increases the paging capacity by reducing the message size and so, the network can serve more number of users compared to the traditional approach. Liu et al. [154] propose a novel user ID-based NB-IoT paging resource allocation scheme to address the issue of load-balancing among paging PRBs in anchor and non-anchor carriers. The authors provide a new definition of paging resource set for paging traffic offloading and also, the corresponding resource selection method. With this scheme, the resource utilization efficiency is increased and the user power consumption is also significantly decreased. To increase the NB-IoT paging success rate, authors in [155] optimize the MCS used for paging in multi-cell interference environment.

6.5.2. Uplink resource management

Similar to DL scheduling, inappropriate UL scheduling also leads to the wastage of resources. To improve the spectrum utilization, Malik et al. [156] formulate a rate maximization problem and consider a resource allocation which accounts for interference, repetition factor, overhead of control channel, and time offset for resource allocation. Their solution improves the data rate by 8% and reduces the energy consumption by 17%. Authors in [78] propose a novel single tone UL scheduling scheme with repetition number determination. In their scheme, inner loop link adaptation guarantees a block error rate by changing the repetition number while the outer loop link adaptation considers MCS level and repetition number based on ACKs/NACKs. The throughput of the system is increased and the transmission reliability is guaranteed by the proposed scheme. Under good channel conditions and large packet size, the proposed scheme performs better than repetition-dominant and straightforward method. It saves more than 14% and 46% of the active time and resource consumption compared to repetition-dominant and straightforward method, respectively. However, their work does not consider multi-tone transmission, time-varying heterogeneous traffic of the IoT devices, and the effects of inter cell interference.

In [157], authors discuss UL resource allocation which allows both multi-tone and single-tone transmission schemes. To provide optimum throughput and fairness, authors consider three different scheduling algorithms: round robin, maximum throughput, and proportionally fair. Jiang et al. [158] propose a UL resource allocation based on Q-learning to optimize, in real-time, the number of IoT users served by NB-IoT network. The authors consider heterogeneous data traffic, selection of coverage level, and RA procedure while scheduling UL resources in NB-IoT network. Authors in [159] propose UL scheduler for NB-IoT system which is user-specific. This work addresses timing management, NPDCCH allocation considering multiple CE levels, and NPUSCH subcarrier allocation. The proposed algorithm decreases the average delay and increases resource utilization of the system. Research work in [160] provides the strategies for sharing radio resources between LTE and NB-IoT. The authors characterize and compare three resource allocation strategies: static, dynamic, and dynamic with reservation, in terms of heterogeneous data traffic and service reliability. The dynamic with reservation strategy provides high resource utilization and guaranteed reliability requirements.

In summary, we can say that efficient DL and UL resource management is required to ensure maximum utilization of available resources. For DL, several authors have identified that optimal usage of NPDCCH resources is vital for increasing the resource utilization efficiency as well as the number of served users. Similarly, some researchers have tried to use different paging techniques with the aim of increasing the number of paged users, increasing paging success rate, managing paging load, etc. In the same way, for UL, selecting optimal MCS level and repetition number, along with proper subcarrier allocation, is needed for maximizing the UL resource utilization. Therefore, significant work has been done, using both traditional and machine learning-based optimization techniques, on selecting these parameters correctly for satisfying various objectives such as maximizing the throughput, increasing the number of served users, allowing fair resource allocation amongst multiple users, etc.

6.6. Interference analysis

The co-existence of NB-IoT with legacy LTE leads to several interference management issues. Research work has been performed in order to mitigate the adverse effects of interference. Resource blanking is an effective interference mitigation technique [161]. In [162], authors analyze the interference caused by legacy LTE to in-band mode NB-IoT and propose an LTE UL scheduling method which reduces the interference faced by NB-IoT. Furthermore, difference in carrier spacing between LTE (15 kHz) and NB-IoT (3.75 kHz in UL) also results in interference [164]. In [164] and [165], authors try to suppress interference between LTE and NB-IoT by equalizing NB-IoT's power per carrier to that of legacy LTE. In [161], authors discuss the issues arising from partial deployment of NB-IoT in the network. Here, the NB-IoT device cannot attach to an appropriate cell if parts of the network do not support NB-IoT. This results in high path loss and high interference to NB-IoT cells from non - NB-IoT cells. Authors in [166] propose a block-sparse Bayesian learning - based approach for Narrowband Interference (NBI) cancellation.

Liu et al. [167] proposed a sparse machine learning approach for accurate NBI recovery. Their proposed algorithm protects both DL and UL transmissions in legacy LTE from NB-IoT interference. If orthogonality between NB-IoT and the underlying legacy LTE system is lost, it also causes interference and results in performance degradation [163]. The authors analyze the interference for LTE users from NB-IoT users and propose a channel equalization algorithm for UL NB-IoT system. Performance of positioning methods like OTDOA is restricted by the interference arising from the neighboring eNBs. In [93], authors propose an iterative expectation maximization-based successive interference cancellation algorithm and use it in a time of arrival detector which is robust against inter-cell interference, fading-channel, and residual frequency-offset. Similarly, Tong et al. [94] study the positioning performance of NB-IoT and conclude that coordination among the participating eNBs can mitigate their interference to the devices.

Hence, we conclude that interference between NB-IoT and legacy LTE networks is mainly caused by partial deployment of NB-IoT, loss of orthogonality between NB-IoT and LTE, and differences in carrier spacing between NB-IoT and LTE. So, interference management is required to reduce the interference to NB-IoT users and to improve the performance of some features like OTDOA. Therefore, several researchers have proposed interference avoidance (resource blanking, customized LTE UL scheduling), interference cancellation, and UL NB-IoT channel equalization algorithms for interference management. Our key finding in the work done in NB-IoT until now is highlighted in Table 6.

Table 6
NB-IoT until now.

Work Area	Related work	Key Findings
Deep Coverage	[7,9,10,76,107–114,141–144]	• Coverage improves by BW reduction and transmitted signal repetition • BW reduction improves PSD and thus, enhances coverage • Signal repetitions improve coverage when channel quality is poor • However, repetitions increase device's battery consumption and reduce throughput
Energy Management	[9,20,22,112,115–127,145]	• Device's battery consumption can be achieved by efficient resource allocation, transmission energy reduction, reducing the number of repetitions, and reducing the time spent in RRC-Connected state • Efficient resource allocation reduces the number of RA attempts and also, the energy consumed in transmitting on radio resources • Transmission energy reduction also degrades transmission reliability and QoS
Random Access Procedure	[128–140]	• RA establishes radio link between eNB and user • RA preamble detection probability analysis is necessary for preamble receiver design • RA preamble collision probability can be reduced by combining RA with spectrum sensing, access class barring, etc. • ToA estimation in RA procedure is improved by frequency hopping
Massive Connections	[20,131,140,146–151]	• Fast-OFDM and NOMA can increase number of users served by NB-IoT • Small data transmission in idle state can help in increasing the number of supported users • Efficient RA procedure increases access success probability, allowing more users to connect simultaneously • Combination of cogitative radio with RA strategies will help in reducing the number of collisions, thereby increasing the number of supported users
Resource Management	[78,97,147,152–160]	• Effective resource management ensures maximum resource utilization • Efficient user-specific NPDCCH resource management is critical for high DL resource utilization • Paging resource management over anchor and non-anchor carriers is also required • Proper UL resource allocation needs to consider NPDCCH resource allocation, repetition number, inter-cell interference, and single-tone/multi-tone subcarrier allocation • Resource allocation can be improved through both traditional approaches (link adaptation, PF scheduling, etc.) and machine learning-based scheduling
Interference Analysis	[93,94,161–168]	• Interference is caused by partial deployment of NB-IoT, loss of orthogonality, and difference in carrier spacing • It can be suppressed by equalizing power per carrier of both NB-IoT and LTE • It can also be avoided by transmission coordination between participating eNBs

7. NB-IoT with other technologies

Combination of NB-IoT with other interesting technologies like D2D, M2M, NOMA, and social IoT helps to improve its performance in various aspects such as network energy consumption, communication latency, number of supported devices, traffic congestion etc.

7.1. Machine-to-machine and device-to-device communication

Chen et al. [169] propose an M2M relay which reduces the number of repetitions in NB-IoT system and hence, saves energy consumption while maintaining system throughput and user QoS. The proposed scheduling mechanism reveals that for transmitting device density of 0.3, the system can save up to 65% of energy consumption. In [145], authors propose a relay selection algorithm to minimize the energy consumed in a NB-IoT cell. An idle user acts as a relay and cooperates in delivering data from another user to the base station. This scheme reduces the total network energy consumption. However, the work did not consider the parameters like throughput, delay, packet scheduling, and re-transmission scheme in performance evaluation. Authors in [170] investigate a scenario where NB-IoT is aided by moving vehicles which relay NB-IoT traffic to base station. They evaluate the performance of their scheme considering parameters like energy efficiency, latency, and communication reliability.

In a heterogeneous network, the link quality of NB-IoT user may not fulfill its QoS requirements. So, the authors in [171] use D2D communication for routing NB-IoT UL transmission, meaning that NB-IoT user's data is sent to the base station via D2D relays. Similarly, authors in [172] used opportunistic multi-hop D2D - based content uploading scheme and also used NB-IoT technology to establish a link between the user and the eNB through D2D for proximity-based transmission. This scheme outperforms traditional schemes in terms of content uploading time, energy consumption, and data loss. Zhang et al. [173] propose a new communication approach based on NB-IoT and LoRa. Here, the communication mode comprises of two nodes: the main node utilizes both the technologies while the sub-node is based on LoRa only. The combination of these two technologies is expected to lower the operating cost of the system and improve the coverage.

In summary, we can say that using M2M relays can be beneficial in an NB-IoT network. Use of M2M relays can reduce power consumption for NB-IoT users as well as decrease their content uploading time. Table 7 summarizes the research on using M2M relays with NB-IoT.

7.2. Non-Orthogonal Multiple Access (NOMA)

The number of NB-IoT devices are increasing at a rapid pace. The available limited network resources are unable to cater to such massive number of devices. Therefore, the requirement to assign resources orthogonally is a bottleneck when the network needs to support a lot of NB-IoT devices. For example, NB-IoT UL uses subcarrier-level data transmission and can serve at most 48 users at particular time (with 3.75 kHz subcarrier spacing) since one user will occupy one subcarrier.

NOMA is a promising approach to solve this problem of limited resource [174,175]. Fig. 16 shows OMA and NOMA scheme for two user scenario. Unlike OMA, the entire bandwidth is shared simultaneously by the two users in NOMA. In NOMA, multiple users share the same subcarrier at a particular time, thereby improving the spectrum efficiency. The two major classifications of NOMA are: power-domain NOMA, where users are multiplexed in power domain and code-domain NOMA, where users are multiplexed in code domain [175]. The other multiplexing techniques are sparse code multiple access inspired by CDMA system, multi-user shared access, and pattern division multiple access [176,177]. Authors in [178] discuss the potential benefits and limitations of NOMA in cellular IoTs. Simulation results in [179] show that NOMA can provide some gain over OMA if data arrival rate is small and the data receiver structure is chosen carefully.

Research Survey: In order to connect a large number of NB-IoT users to the network, Mostafa et al. [148] propose a power-domain NOMA

Table 7
NB-IoT with other technologies.

Work area	Related work	Key findings
M2M and D2D	[145,169–173]	• Possible to combine NB-IoT with M2M and D2D • Improves performance in terms of energy consumption, latency, and reliability • Prevents data loss and reduces system operating cost
NOMA	[148,180–183]	• Multiple users share same sub-carrier, thus improving the spectrum efficiency • Improves throughput and lowers latency • Can meet NB-IoT requirements for massive number of connections and higher spectral efficiency
Social NB-IoT	[172,185,186]	• Solves issues related to security, reliability, and traffic congestion • Reduces negative influence of malicious nodes and thus improves reliability and security of data transmission • Lowers latency and energy consumption of device • Increases number of users served and decreases outage probability
NB-IoT in 5G NR	[149,187–194]	• 5G NR provides several advantages over LTE, for example, higher throughput, lower latency, and improved QoS handling • Multi-access 5G core network can support LTE, NB-IoT, and 5G IoT • 5G technologies such as Fast-OFDM and SEFDM can increase the number of connected devices without compromising on data rate and receiver complexity • 5G may also support fast authentication service for NB-IoT, which will reduce access time and power consumption of NB-IoT devices

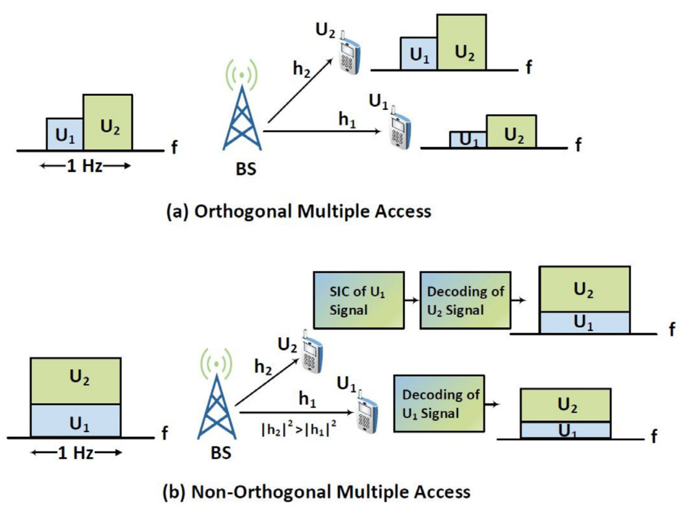

Fig. 16. Orthogonal and non-orthogonal multiple access.

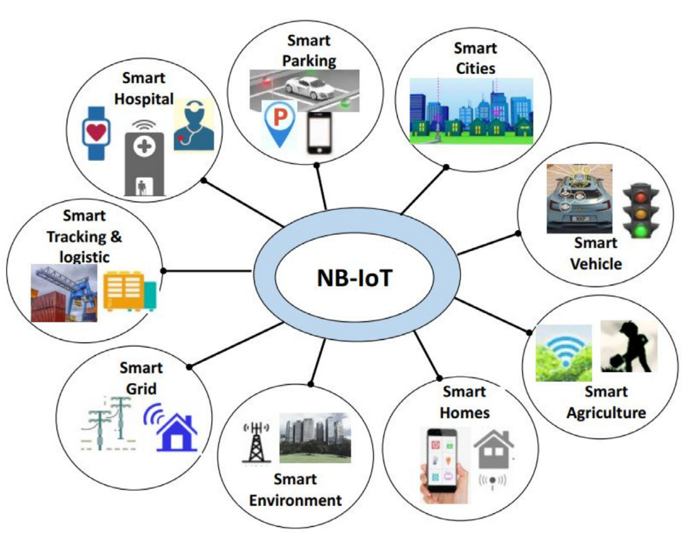

Fig. 17. Applications of NB-IoT.

scheme which supports a higher connection density compared to OMA while maintaining the QoS requirements. The authors jointly allocate sub-carriers and transmission power to the devices with an aim to maximize the number of devices connected to the network. Similarly, authors in [180] apply power-domain NOMA to an NB-IoT network which uses Mobile Edge Computing (MEC). They propose to minimize the maximum task execution latency using an algorithm which jointly optimizes the MEC computation resource allocation and the successive interference cancellation ordering of NB-IoT devices. However, this work does not include dynamic optimization of device scheduling, where NB-IoT devices can mutually decide which devices will transmit together and their duration of data transmission.

In [181], the authors consider the DL of a NOMA-based network and formulate a user scheduling and power allocation problem which is solved using Lyapunov optimization technique. The proposed scheme makes decisions based on real-time system state and leads to improvement in power consumption as well as user satisfaction. Authors in [182] consider NOMA with random packet arrival scenario in a network supporting massive IoT. Their simulation results demonstrate that, unlike NB-IoT which supports 18 packets per second for UL latency of approximately 2.8 s, NOMA can support an arrival rate of 100 packets per second for delay requirement of 100 ms. and 180 packets per second for the delay requirement of 1 s. Similarly, authors in [183] apply user clustering to power-domain NOMA in order to maximize the throughput and increase the number of devices connected to the network through optimum resource allocation to MTC devices. Authors in [184] design non-orthogonal spectral efficient frequency division multiplexing waveform for single and multiple antenna systems and show that it can enhance DL throughput by 11% as compared to NB-IoT.

Thus, we conclude that NOMA can be a promising solution for supporting a large number of devices concurrently with NB-IoT. Researchers have applied several techniques to combine NOMA with NB-IoT and have shown that NOMA can potentially increase the number of users supported by NB-IoT. Nevertheless, a lot of research needs to done to overcome the limitations of applying NOMA in an NB-IoT network. Table 7 summarizes the research on using NOMA with NB-IoT.

7.3. Social NB-IoT

The fast increasing use cases for IoT can be supported by NB-IoT and D2D technologies. However, there are some issues of security, reliability, and traffic congestion associated with these technologies which can be mitigated to some extent using the concept of social IoT. The concept of social relationship is presented in [195]. The authors have discussed two types of trustworthy models: a subjective model, which is based on individual experience and the experience of a common friend, and an objective model, where each nodes's information is stored in a hash table structure and is distributed to other nodes. The inclusion of this concept enhances the efficiency of the network in terms of network scalability and security. However, due to feedback exchange messages, there is an increase in network traffic.

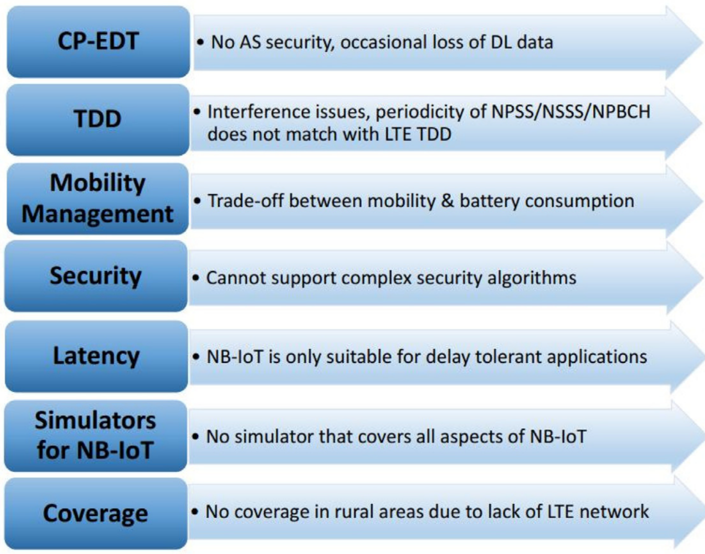

Fig. 18. Open issues in NB-IoT.

Inspired from Social IoT (S-IoT), social awareness concept has been introduced in NB-IoT [185]. In this paper, the authors consider the level of trust among the devices connected in the network and model it using the concepts of reputation and reliability concepts. They have applied S-IoT concepts to NB-IoT and D2D communication, which has helped in saving the energy of the device, providing secure data transmission, and traffic offloading. In their approach, NB-IoT is used to establish a link between the user and the eNB. Then, cooperative multi-hop D2D is used for uploading data to eNB. With the notion of trust, the malicious nodes present in the network can be handled. The authors show that the social awareness among the devices can reduce the negative effect caused by the malicious nodes. It also leads to lower data loss, higher gain in content uploading time, and lower energy consumption.

Furthermore, in [172], the authors exploit the advantages of NB-IoT and D2D communication. They consider short range multi-hop relaying for uploading content to the base station. They use NB-IoT to establish a link between the user and base station and use D2D communication to establish connections between the devices in close proximity. They utilize the S-IoT concept to establish trustworthy relationship among the devices to detect the malicious behaviors of the users and evaluate model performance through several parameters including reduction in data loss, lower average energy consumption, and lower data uploading time. Analysis using the trust-based solution shows that the data loss is 19% less compared to the data loss with the conventional approach.

Ning et al. [186] propose a group formation mechanism based on social awareness. The authors develop a social-aware, D2D-enabled NB-IoT cooperative framework referred to as SAGA and use it to upload information to the eNB. For resource allocation, they formulate an optimal group game considering the constraints like cost, transmission power, network load, etc. Their proposed scheme increases the number of served users and decreases the outage probability and the transmission power.

In summary, we can say that social IoT is useful for security and reliability of NB-IoT network and can reduce the influence of malicious nodes in the network. Research so far has shown that social IoT can not only support secure data transmission but can also be useful for offloading traffic, reducing data loss, and decreasing UL round-trip time. Table 7 summarizes the research on using social IoT with NB-IoT.

7.4. NB-IoT in 5G NR

5G NR technology aims to deliver high data rates with very less latency, increased base station capacity, and improved QoS compared to LTE [196]. The 5G technology will significantly improve the network performance, scalability, and efficiency and will reduce end to end latency [197]. Palattella et al. [198] present NB-IoT as an important technologies for connecting IoT devices in 5G era. 3GPP has now made NB-IoT a part of 5G [65,199]. The performance of 5G-NR, LTE-M and NB-IoT was evaluated by 3GPP which reveals that LTE-M and NB-IoT can support density requirement of 1 million devices per square kilometers with the maximum latency of 10 s [200]. The multi-access 5G core network will provide connectivity to LTE, NB-IoT, and 5G IoT. In the 5G specifications, 3GPP has covered four major user cases [194,201]:

- *Ultra Reliable Low Latency Communications (URLLC):* It aims to provide high communication quality with latency as low as 1 ms. The data transmitted is both reliable and accurate. The major applications of URLLC include real-time monitoring, V2X, smart grid etc.
- *Enhanced Machine Type Communication (mMTC):* This feature is suitable for applications where an extremely large number of IoT devices are involved and aims to establish inter-connection among all things. The devices should have low cost and very long battery life.
- *Enhanced Mobile Broadband (eMBB):* This is suitable for the use-cases which require high data rate and seamless user experience. The usage scenario includes wide-area coverage and hot-spots. The applications include 4K HD videos, virtual and augmented reality, telemedicine etc.
- *NR-Light:* It is scheduled to be included in 3GPP Rel-17 and will target IoT markets, such as video surveillance cameras and industrial wireless sensors, which cannot be serviced by LPWA devices intended for mMTC use-case [202]. These IoT devices have UL-dominated traffic and require higher data rate, more frequent data transmission, and lower battery life than LPWA devices. They need to be more complex than LPWA devices but do not require to be as complex as eMBB or URLLC devices.

Research Survey: Authors in [149] propose Fast-OFDM which can increase the number of connected devices by two times without lowering the data rate or increasing the bit error rate. The proposed scheme provides 50% bandwidth saving compared to the SC-FDMA. Authors in [187] propose non-orthogonal multi-carrier spectrally-efficient frequency division multiplexing signal waveform. It can enhance the throughput of the next generation of NB-IoT devices by about 11% while having computational complexity similar to the present-day receivers. Authors in [188] indicate that the functional architecture of NB-IoT can be integrated into upcoming 5G network.

Javaid et al. [189] present the enablers and challenges of 5G-IoT. They mention that IoT-based 5G network should support low-power communication to enable efficient power consumption for massive number of IoT devices. Authors in [190] consider NB-IoT a promising technology in meeting the requirements of massive IoT in 5G era. Currently, NB-IoT devices use the traditional 3GPP standard authentication process which adds a lot of overhead during NAS authentication of NB-IoT device. In [191], authors describe fast mutual authentication which can lead to faster data transfer for NB-IoT devices. Authors in [192] consider 5G heterogeneous networks and evaluate the performance of NB-IoT in such a network deployment in terms of throughput and power consumption. mMTC uses cases are expected to be handled by NB-IoT while 3GPP Rel-15 specifications will focus on supporting MBB and URLLC [193,194].

In summary, NB-IoT has now been made a part of 5G technology by 3GPP. Research on use of 5G NR with NB-IoT indicates that use of 5G techniques, such as Fast OFDM and SEFDM, can increase the number of devices supported by NB-IoT while also maintaining the required data rate and low device complexity. Use of NB-IoT with 5G may also offer other benefits such as fast authentication of NB-IoT devices. Table 7 summarizes the research on using NB-IoT in 5G networks.

8. Applications of NB-IoT

As depicted in Figure 17, there is a tremendous increase in the variety of low-power applications in today's scenario.

8.1. Smart hospitals

The emergence of cellular IoT has led to the introduction of smart devices and infrastructure in hospitals. Zhang et al. [203] propose that, in a smart hospital, NB-IoT can be used to connect smart things with each other. These things include intelligent monitoring center, smart meter reading, out-patient clinic, pharmacy, smart parking etc. The concept of smart hospitals works effectively in two scenarios: (i) Clinical care, where the patient is admitted to the hospital, and (ii) remote care, where the patient's blood pressure, heart beat etc. can be monitored remotely [204]. However, there are several challenges due to which NB-IoT is only partially suitable for health care [205]. These include high latency (which affects the accuracy and reliability of data), data security and privacy, high cost, hospital security, etc. In [22], authors present a case study to demonstrate energy-efficient adaptive health monitoring system using NB-IoT. The proposed scheme can provide continuous monitoring of the patient and can keep a track of patients' health.

8.2. Smart parking

Parking is a challenging issue in several regions, specially in big cities. A smart parking ecosystem ensures reduction in traffic congestion and rapid search of parking space, thus providing better parking management. Lin et al. [206] provide a detailed literature survey on the deployment of smart parking systems. The smart parking solutions are characterized by collection of information, deployment of system, and service distribution. With an objective of improving user payment experience and reducing the deployment cost, authors in [207] consider an NB-IoT - based parking solution where the proposed system consists of sensor nodes in the parking space, a cloud server to provide information about the surroundings, a device application for the users, and a payment process. Similarly, in [208], authors propose NB-IoT system and wireless sensor network-based urban smart parking management platform. Companies like Qualcomm, Huawei, Ericsson, and Mediatek are also developing NB-IoT solutions for smart parking [206].

8.3. Smart cities

Development of smart cities is an important use-case of cellular IoT, since it involves numerous inter-connected IoT devices [84]. The primary aims of this concept are smart waste management, smart traffic management, air quality monitoring, and inter-connection of various smart public facilities like electricity meters, etc. [9]. Zhao et al. [210] propose an NB-IoT - based street light system which saves energy and is cost-effective. In the proposed scheme, authors combine power line communication and NB-IoT network to provide intelligent control of LED street lights. Furthermore, automatic garbage deployment is another application of NB-IoT [211]. Authors propose an automatic garbage detection and recognition system using deep learning and NB-IoT network. The proposed technique is better than the traditional garbage monitoring technique in terms of cost and material resource. Also, the accuracy of garbage detection and recognition is better than the traditional approach. Authors in [212] propose a smart framework which uses NB-IoT and edge computing to monitor smart trash cans.

8.4. Smart vehicles

Internet of Vehicles (IoV) is another use case of NB-IoT. Authors in [213] propose an NB-IoT network-based car networking data acquisition scheme. The network architecture includes NB-IoT devices, base station, core network, cloud platform, back-end server, and traffic management platform. The proposed scheme can access real-time traffic information as well as control the speed of vehicle by giving warnings on over-speeding. It provides better safety to drivers because it helps to avoid traffic congestion and accidents. Authors in [16] consider NB-IoT an appropriate solution in cities where the number of DL messages increases because of traffic congestion, road accidents, broken-down cars etc. Authors in [226] explain that merging V2X with NB-IoT can improve its potentials. Authors consider NB-IoT devices like smart bicycles and smart traffic cones as relays. A vehicle can notify its location to the NB-IoT device which, in turn, can transmit alert messages to another vehicle close to it. This results in efficient utilization of narrowband resource.

8.5. Smart agriculture

Smart agriculture is also an interesting applications of NB-IoT. The primary objective of an agricultural farm is to maximize the yield and reduce the production and input costs [214]. Authors in [22] present a case study to demonstrate the utilization of water for irrigation purpose in an energy-efficient manner. Soil moisture sensors installed in the farm gather data and send it to the NB-IoT cloud using NB-IoT base station. Deep learning algorithm is used to process data and helps to adaptively divides the farm into zones on the basis of moisture content in the soil. Smart NB-IoT - enabled water control device is attached to the water pump to transmit the desired quantity of water for the desired time. After that, the sensor nodes attached to the zones having appropriate moisture level enter the sleep state. This saves energy, controls UL traffic, and reduces traffic congestion.

8.6. Smart homes

Other innovative use cases of cellular IoT include smart homes. Authors in [215] provide applications of NB-IoT in smart home scenario. Smart home includes energy consumption management, live chat, home security, smart metering etc. Smart metering helps to reduce manpower by remotely and automatically collecting data over the cellular network. Pennacchioni et al. [216] propose a deployment analysis of NB-IoT system for smart metering. They consider three different classes of metering: energy metering, air quality monitoring, and outdoor smart parking. The performance of this system in analyzed terms of capacity, coverage, and system efficiency. In [217], authors propose a remote monitoring system for indoor environment using NB-IoT technology. The system remotely monitors light intensity, humidity, temperature etc.

8.7. Smart environment

NB-IoT solution for remotely monitoring water level in industries is introduced in [218]. The scheme remotely monitors the water level in real-time using NB-IoT and transmits it over the narrowband frequency. It ensures effective utilization of resources and reduction in cost. Authors in [219] present an NB-IoT solution for water monitoring system in rural Malaysia. Duangsuwan and team develop smart sensors which transmits data through NB-IoT network. These sensors are used for monitoring air pollution by detecting the pollution index and help in knowing the real-time air quality. Each sensor includes air-quality detection sensors, micro-controller, NB-IoT device, database, and web monitoring system [220,221]. Wildlife tracking is very useful for several purposes like conservation of endangered species, environment monitoring, animal disease monitoring, etc. [16]. It is difficult to track wildlife using other methods but it can be easily done using NB-IoT devices.

8.8. Smart grid

Features like low power, deep coverage, and support for massive connections have led to the introduction of NB-IoT solution for smart grid communication. Li et al. [222] investigate the performance of NB-IoT for smart grid communication in both rural and urban areas. Authors conclude that NB-IoT can provide highly reliable long-range communication service with an appropriate throughput. However, NB-IoT is only partially suitable for this application because of certain limitations such as high latency, which make it less suitable for real-time applications. Authors in [223] discuss the suitability of NB-IoT for smart grid applications. They concentrate on technology modelling of NB-IoT to deliver outage restoration and management message in case of power outage in smart grid. The proposed model ensures reliability and timely delivery of the message. In [224], authors present the capacity analysis of smart grid application using both M2M and NB-IoT solutions.

8.9. Smart tracking and logistics

NB-IoT devices are also used for logistics and tracking of assets, vehicles, animals, etc. The location and delivery information of the goods can be tracked in real-time using NB-IoT devices. Samsung has launched smart tracking tags which use NB-IoT network [225].

To summarize, NB-IoT has been widely adopted by various companies in several different scenarios. NB-IoT has enabled hospitals to take care of their patients more efficiently. It has also been deployed in several other urban scenarios such as parking systems, street lighting systems, and garbage collection systems. Another envisaged use-case for NB-IoT is Internet of Vehicles, where NB-IoT can be used to avoid traffic congestion and accidents. In smart homes, NB-IoT supports smart metering, security functions, and indoor environment monitoring. Apart from these uses, NB-IoT has been deployed in diverse fields such as agriculture, pollution monitoring, electricity grid monitoring, and goods tracking. The applications of NB-IoT are summarized in Table 8.

9. Open issues and future scope

NB-IoT is a promising LPWA technology and the use cases of NB-IoT are continuously increasing. Being a new technology, there are a few limitations and restrictions associated with it. They need to be investigated so that NB-IoT can support all its conceived use-cases. Therefore, in this section of our review, we discuss some open issues of NB-IoT which are summarized in Figure 18.

9.1. Control Plane Early Data Transmission (CP-EDT)

CP-EDT, standardized in 3GPP Rel-15, allows UL and DL data transmission during RA procedure. There is no AS security in CP-EDT. Both the UL and DL data are transmitted by piggybacking it on the NAS message in the RRC message sent over Signalling Radio Bearer-0 (SRB0), which is not associated with RLC ARQ re-transmission [103]. Originally, when the RRC Early Data Complete message is received, there is no confirmation message sent by the user about the reception of this message. Since transmission failure of this message is handled using only MAC layer HARQ re-transmission, the users in poor coverage are likely to suffer from DL transmission failure [103,146]. In 3GPP Rel-15 mobile-originated EDT (MO-EDT), it is proposed that the downlink message transmitted in RRC Early Data Complete can be an application acknowledgement (TCP ACK) [227]. Furthermore, in 3GPP Rel-16, mobile-terminated EDT (MT-EDT) will be introduced and will allow the eNB to send user data in Msg-4. In this case, a further acknowledgement message from the user to the eNB will be required after Msg-4 to increase the reliability of data transmission.

9.2. Time division duplex

Until 3GPP Rel-13 and Rel-14, NB-IoT supported only the FDD mode which meant that all available spectrum could not be utilized for NB-IoT. In 3GPP Rel-15, TDD mode is introduced for both UL and DL data transmission to optimize the use of available spectrum. Although there are several advantages delivered by NB-IoT TDD, there are also a few issues associated with TDD support [101]. Firstly, for in-band and guard-band deployment modes, NB-IoT TDD networks will cause interference to LTE FDD networks as well as even LTE TDD networks (if NB-IoT and LTE TDD configurations are different). Secondly, periodicity of NPSS, NSSS, and NPBCH may not match with LTE TDD DL subframe configuration [101]. These points should be considered during down-selection of NB-IoT TDD configuration.

9.3. Mobility management

Up to 3GPP Rel-15, limited mobility is offered by NB-IoT. Unlike conventional LTE, an explicit handover is not supported for NB-IoT users. The user has to connect to the network again if RRC Connection Resume and RRC Connection Re-establishment procedures fail. This decreases the battery life of the device. There are several applications like remote patient monitoring, smart goods tracking, wildlife tracking, and smart vehicles etc. which require mobility support. For instance, if the patient moves at a high speed, NB-IoT solution is not suitable since it only supports low speed mobility and has communication latency which restricts quickly switching between gateways [16]. Similarly, for smart vehicles, goods tracking, and wildlife tracking, the support of mobility is essential. Due to the limited mobility support, mobile operators must optimize cell re-selection performance in order to provide NB-IoT service reliably [228]. Authors in [228] provide a method for NB-IoT cell re-selection. Simulation results reveal that the shorter paging DRX and re-selection timers will give better mobility performance but will deteriorate the battery consumption of the users. Therefore, there is a trade-off between battery consumption of the devices and the extent of mobility they can support. It is an important area that needs to be investigated further.

9.4. Security

Security is also a primary concern of the NB-IoT system. Due to simple architecture and limited resources like bandwidth and battery power, NB-IoT devices cannot support complex security algorithms at all the layers of the network [229]. Also, if NB-IoT devices are used in D2D communication, they may face the issue of eavesdropping and may be attacked by malicious nodes [172]. So, the security-related risks in

Table 8
Applications of NB-IoT.

Applications	Related work	Key Findings
Smart Hospitals	[22,203–205,209]	• NB-IoT - based smart hospitals have inter-connected patient monitoring centers, out-patient clinics, pharmacies, etc. • They can handle clinical care in hospital as well as remote care of the patient • However, NB-IoT - based healthcare has a few limitations due to issues like high latency, data security, etc.
Smart Parking	[206,207,208]	• NB-IoT - based smart parking systems allow rapid search of parking spaces • They also lower the deployment cost and improve user experience • These systems usually consist of sensor nodes, a cloud server, a device application for users, and a payment process • Companies like Qualcomm, Ericsson etc. are developing NB-IoT solutions for smart parking
Smart Cities	[9,84,210–212]	• Cities use a large number of inter-connected NB-IoT devices for waste management, traffic management, air quality monitoring, etc. • For example, smart street light control system based on power line communication and NB-IoT helps to save energy • Similarly, smart garbage detection systems based on deep learning and NB-IoT perform better at garbage recognition and also reduce deployment cost and required material resources
Smart Vehicles	[16,213]	• NB-IoT - based Internet of Vehicles provides real-time traffic information to drivers, control over-speeding, and reduce traffic congestion and accidents • NB-IoT - based smart devices like traffic cones and bicycles help in rapid dissemination of alert messages through relaying
Smart Agriculture	[22,214]	• NB-IoT - based smart solutions for agriculture maximize the yield and lower the input costs • For example, NB-IoT - based sensor network can be deployed for efficient management of water used for irrigation
Smart Homes	[215–217]	• NB-IoT can be used for smart metering, home security, reducing energy consumption of home appliances, etc. • It can also be used for remote monitoring of indoor environment like light intensity, humidity, temperature, etc.
Smart Environment	[16,218–221]	• NB-IoT is used in several ways for smart environment management • For example, it is used in remote water level monitoring in industries and in air pollution monitoring • It is also used for tracking wild animals
Smart Grid	[222–224]	• The communication range, data rate, and reliability of NB-IoT are appropriate for smart electricity grids • For example, NB-IoT can be used to deliver outage restoration and management messages in case of power outage • However, NB-IoT does not support well some smart grid applications requiring low latency
Smart Tracking and Logistics	[225]	• NB-IoT - based smart tags are used for tracking of assets, vehicles, and animals

NB-IoT need to be handled before NB-IoT devices can be used in scenarios such as D2D communication.

9.5. Latency

NB-IoT supports mainly delay-tolerant applications and is not fit for applications which require real-time monitoring. For example, in a smart grid system, NB-IoT solution is less suitable as it cannot transmit critical real-time information in emergency cases like fault occurrence, system instability, etc[222]. Similarly, in case of smart hospitals, there are a large number of parameters which require monitoring in real-time and with low latency. NB-IoT is not suitable for such applications [203]. Therefore, communication latency reduction needs to be investigated and is one of the major considerations of 3GPP Rel-15 [101].

9.6. Simulator in NB-IoT

Due to the rapid and wide-spread adoption of NB-IoT, many good simulators have been developed for NB-IoT. However, this is an ongoing effort and further progress is needed to develop simulators which cover all aspects of NB-IoT. Authors in [230] have created an NB-IoT simulator based on the open-source LTE-sim tool. This simulator mainly supports some features of the physical layer of NB-IoT, along with a few scheduling algorithms. However, some important features like single-tone transmission, multi-tone transmission, repetitions, errors in physical layer, and more accurate channel models need to be supported. Another open-source software, srsLTE, supports all physical layer NB-IoT channels [231]. However, it does not support channel coding, modulation, and demodulation. MATLAB supports an extensive toolbox for modelling the NB-IoT physical layer. Using this toolbox, all physical and transport channels, along with modulation and coding, can be simulated. In [232], the authors have developed a mathematical model of various aspects of the physical layer and then, tested their model using MATLAB simulations. Visual system simulator software, developed by National Instruments, is another commercial software available to telecom operators for NB-IoT physical layer system design. However, MATLAB and VSS are commercial softwares and may not be available to all researchers.

In [122], the authors have developed an end-to-end NB-IoT simulation framework based on the open-source NS3 software. NS3 already has a well-tested LENA module for LTE. The authors have outlined the differences between LTE and NB-IoT. But, while creating an NB-IoT simulator, they have incorporated only a few of these differences in the LENA module. In [124], the authors have developed a mathematical model for PSM and eDRX. Then, they have validated their model using NS3 simulations. Similarly, further work is required to incorporate other important MAC and RLC layer NB-IoT features in simulators. In [233], the authors have described use-cases like smart metering and smart cities for NB-IoT and are in the process of implementing the required simulation framework in OMNET + +, another open-source software for end-to-end simulation. However, the implementation is not finished and so, their framework is not yet available for use. In [234], the authors have implemented a basic NB-IoT model in OPNET software and have verified important NB-IoT characteristics like delay, channel utilization, and coverage area. Atoll software from Forsk supports NB-IoT network modelling, traffic modelling, automatic frequency planning, cell planning, and site positioning. Similar to MATLAB and VSS, OPNET and Atoll are also commercial softwares and may not be available to all researchers.

9.7. Coverage

Due to the lack of LTE network in the rural areas, the coverage is restricted. If a logistic site is located in a rural area, there may be no LTE network coverage available there. NB-IoT technology is not fully compatible with applications like smart farming and wildlife tracking due to the lack of cellular signal and coverage [16]. It is imperative to have excellent coverage to satisfy the requirements of both massive and critical IoT applications [65].

10. Conclusion

In recent years, the introduction of new IoT applications, like smart grids, smart vehicles, smart industries etc., has caused a sharp increase in the number of IoT devices. The introduction of LPWA technologies has played a vital role in catering to the demands of these devices. In our survey, we provide a comprehensive review of NB-IoT which is a cellular technology meant to support low-complexity and low-power devices working in areas of poor coverage. We describe the NB-IoT architecture which was introduced in 3GPP Rel-13 and then, we discuss the enhancements made in subsequent 3GPP releases, up to3GPP Rel-16. Next, we exhaustively survey the research work done on various aspects of NB-IoT, including support for deep coverage, energy management, massive number of devices, random access, radio resource management, and interference mitigation. Furthermore, we describe how some other interesting technologies like D2D, M2M, NOMA, and 5G NR, are being coupled with NB-IoT to further enhance its performance. Subsequently, we highlight several scenarios in which NB-IoT - based systems have been deployed in practice. Finally, we identify a few existing short-comings which need to be eliminated through further research work.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

Eshita Rastogi: Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Navrati Saxena:** Conceptualization, Writing - review & editing, Visualization, Supervision, Project administration. **Abhishek Roy:** Visualization, Writing - review & editing, Investigation. **Dong Ryeol Shin:** Resources, Supervision, Funding acquisition.

References

[1] U. Raza, P. Kulkarni, M. Sooriyabandara, Low power wide area networks: an overview, IEEE Commun. Surv. Tutor. 19 (2) (2017) 855–873.
[2] NB-IoT, Document RP-151621, 3GPP TSG RAN Meeting #69, Technical Report, 2015.
[3] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 13.12.0
[4] W. Yang, M. Wang, J. Zhang, J. Zou, M. Hua, T. Xia, X. You, Narrowband wireless access for low-power massive internet of things: a bandwidth perspective, IEEE Wireless Commun. 24 (3) (2017) 138–145.
[5] A. Petroni, F. Cuomo, L. Schepis, M. Biagi, M. Listanti, G. Scarano, Adaptive data synchronization algorithm for IoT-oriented low-power wide-area networks, Sensors 18 (11) (2018) 4053.
[6] Technical Specification Group GSM/EDGE Radio Access Network; Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT), Technical Report (TR), 3rd Generation Partnership Project (3GPP), 2015. Version 13.1.0
[7] M. Lauridsen, I.Z. Kovács, P. Mogensen, M. Sorensen, S. Holst, Coverage and capacity analysis of LTE-M and NB-IoT in a rural area, in: Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th, IEEE, 2016, pp. 1–5.
[8] Y.D. Beyene, R. Jantti, O. Tirkkonen, K. Ruttik, S. Iraji, A. Larmo, T. Tirronen, J. Torsner, NB-IoT technology overview and experience from cloud-RAN implementation, IEEE Wireless Commun. 24 (3) (2017) 26–32.
[9] J. Xu, J. Yao, L. Wang, Z. Ming, K. Wu, L. Chen, Narrowband internet of things: evolutions, technologies, and open issues, IEEE Internet Things J. 5 (3) (2018) 1449–1462.
[10] Y.D. Beyene, R. Jantti, K. Ruttik, S. Iraji, On the performance of narrow-band internet of things (NB-IoT), in: Wireless Communications and Networking Conference (WCNC), 2017 IEEE, IEEE, 2017, pp. 1–6.
[11] M.S. Ali, Y. Li, M.K.H. Jewel, O.J. Famoriji, F. Lin, Channel estimation and peak-to-average power ratio analysis of narrowband internet of things uplink systems, Wirel. Commun. Mobile Comput. 2018 (2018).
[12] N. Živic, Improved up-link repetition procedure for narrow band internet of things, in: 2017 International Conference on Computational Science and Computational Intelligence (CSCI), IEEE, 2017, pp. 1284–1289.
[13] M. Chen, Y. Miao, Y. Hao, K. Hwang, Narrow band internet of things, IEEE Access 5 (2017) 20557–20577.
[14] M. Elsaadany, A. Ali, W. Hamouda, Cellular LTE-A technologies for the future internet-of-things: physical layer features and challenges, IEEE Commun. Surv. Tutor. 19 (4) (2017) 2544–2572.
[15] H. Wang, A.O. Fapojuwo, A survey of enabling technologies of low power and long range machine-to-machine communications, IEEE Commun. Surv. Tutor. 19 (4) (2017) 2621–2639.
[16] W. Ayoub, A.E. Samhat, F. Nouvel, M. Mroue, J.-C. Prévotet, Internet of mobile things: overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and supported mobility, IEEE Commun. Surv. Tutor. (2018).
[17] C.B. Mwakwata, H. Malik, M.M. Alam, Y.L. Moullec, S. Parand, S. Mumtaz, Narrowband internet of things (NB-IoT): from physical (PHY) and media access control (MAC) layers perspectives, Sensors 19 (11) (2019) 2613.
[18] Towards massive machine type communications in ultra-dense cellular iot networks: current issues and machine learning-assisted solutions, IEEE Commun. Surv. Tutor. (2019).
[19] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, J.-P. Koskinen, Overview of narrowband iot in LTE rel-13, in: Standards for Communications and Networking (CSCN), 2016 IEEE Conference on, IEEE, 2016, pp. 1–7.
[20] P. Andres-Maldonado, P. Ameigeiras, J. Prados-Garzon, J. Navarro-Ortiz, J.M. Lopez-Soler, Narrowband IoT data transmission procedures for massive machine-type communications, IEEE Netw. 31 (6) (2017) 8–15.
[21] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, M. Ayyash, Internet of things: a survey on enabling technologies, protocols, and applications, IEEE Commun. Surv. Tutor. 17 (4) (2015) 2347–2376.
[22] S. Popli, R.K. Jha, S. Jain, A survey on energy efficient narrowband internet of things (NBIoT): architecture, application and challenges, IEEE Access (2018).
[23] *MT2625 Ultra-low power, 3GPP Release-14 enabled NB-IoT platform for wide-ranging home, civic, industrial or mobile applications*, 2018.
[24] *MT2621 Dual mode NB-IoT, GSM/GPRS platform for smart trackers, wearables, IoT security and industrial applications*, 2018.
[25] *Breaking through in the crowded IoT market with NB-IoT*, (https://www.mediatek.com/blog/breaking-through-in-the-crowded-iot-market-with-nbiot).
[26] I. Qualcomm Technologies, Paving the path to narrowband 5G with LTE internet of things (IoT), 2016.
[27] I. Qualcomm Technologies, Leading the LTE IoT evolution to connect the massive internet of things, 2018.
[28] *MDM9206 IoT Modem*, (https://www.qualcomm.com/products/mdm9206-iot-modem).
[29] *Overview of NB-IoT chipset vendor's offerings*, (https://haltian.com/news/nb-iot-chipset-vendor-overview/).
[30] *Ericsson broadens NB-IoT reach with MediaTek, Qualcomm launches new chips*, (https://www.mobileeurope.co.uk/press-wire/ericsson-broadens-nb-iot-reach-with-mediatek-qualcomm-launches-new-chips).
[31] *DISH selects Ericsson for NB-IoT radio access and core network, including radio frequency design*, (https://www.ericsson.com/en/press-releases/6/2018/dish-selects-ericsson-for-nb-iot-radio-access-and-core-network).
[32] *Ericsson and Telstra complete ground-breaking long-range NB-IoT connection*, (https://www.ericsson.com/en/press-releases/2018/9/ericsson-and-telstra-complete-ground-breaking-long-range-nb-iot-connection).
[33] *Connecting care: Enhancing healthcare services in China through connectivity and collaboration*, (https://www.ericsson.com/en/cases/2017/astrazeneca).
[34] *Huawei launches new double-capacity Release-14 NB-IoT solution*, (https://enterpriseiotinsights.com/20180606/nb-iot/huawei-launchs-new-nbiot-solutions-tag23).
[35] *Huawei betting on NB-IoT, planning large-scale commercialization in 2017*, (https://enterpriseiotinsights.com/20161101/carriers/huawei-nb-iot-tag23-2).
[36] *Huawei expects big shipments of NB-IoT chips next month*, (https://enterpriseiotinsights.com/20170519/nb-iot/20170519nb-iothuawei-ship-large-volumes-nbiot-chip-next-month-tag23).
[37] *NB-IoT is cheap in China from as little as $ 3 per module*, (https://enterpriseiotinsights.com/20190725/channels/news/nb-iot-is-cheap-in-china-says-huawei).
[38] *Samsung and KT Sign Contract to Supply NB-IoT Solutions that Accelerates Operators Nationwide IoT Service Launch*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=11548).
[39] *Samsung and KT to Launch NB-IoT Pilot Service for Friendly-Users*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=12003).
[40] *Samsung releases first cellular IoT mobile device 'Connect Tag' for multi-purpose tracking*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=12844).
[41] *Samsungs Exynos i S111 Delivers Efficiency and Reliability for NB-IoT Devices*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=13904).
[42] *KT and 'Dalim Special Vehicle' to launch commercial NB-IoT-empowered gas metering service at the end of September*, (https://www.netmanias.com/en/post/korea_ict_news/12776).
[43] *KT demonstrated the world's first NB-IoT-based service*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=10727).
[44] *KT shaping IoST strategies - focusing on NB-IoT*, (https://www.netmanias.com/en/?m=view&id=blog&no=11154).
[45] *KT-Nokia showcased NB-IoT technologies on the commercial LTE network*, (https://netmanias.com/en/post/korea_ict_news/10418).

[46] *LG U+ to deploy NB-IoT-dedicated network*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=11032).
[47] *South Korean government finalized amended NB-IoT standards aiming to launch the world's first, commercial NB-IoT network in June*, (https://www.netmanias.com/en/?m=view&id=korea_ict_news&no=11989).
[48] *Five ways that NB-IoT is changing the world*, (https://www.vodafone.com/business/news-and-insights/blog/gigabit-thinking/five-ways-that-nb-iot-is-changing-the-world).
[49] *Vodafone expands its NB-IoT coverage*, (https://www.gsma.com/iot/rollout-vodafone/).
[50] *Vodafone NZ turns on NB-IoT, LTE-M networks*, (https://www.mobileworldlive.com/asia/asia-news/vodafone-nz-turns-on-nb-iot-lte-m-networks/).
[51] *UK water utility connects to Vodafones NB-IoT network to stop leakages*, (https://enterpriseiotinsights.com/20190726/channels/news/uk-water-utility-connects-to-vodafone-nb-iot-network).
[52] *Vodafone Idea Readies NB-IoT Services in India*, (https://www.lightreading.com/iot/vodafone-idea-readies-nb-iot-services-in-india/d/d-id/755409).
[53] *AT&T Complements LTE-M with the Launch of Nationwide NB-IoT Network*, (https://www.thefastmode.com/technology-solutions/14670-at-t-complements-lte-m-with-the-launch-of-nationwide-nb-iot-network).
[54] *AT&T Lights Up NB-IoT Network Across the U.S.*, (https://about.att.com/innovationblog/2019/04/nbiot_network_live.html).
[55] *AT&T, Vodafone Bridge IoT Networks Across US, Europe*, (https://www.sdxcentral.com/articles/news/att-vodafone-bridge-iot-networks-across-u-s-europe/2019/10/).
[56] *China Mobile rolls out NB-IoT in five cities*, (https://www.gsma.com/iot/rollout-china-mobile/).
[57] *China Mobile pilots NB-IoT for smart parking, smart lighting and water quality monitoring*, (https://www.gsma.com/iot/mobile-iot-pilots-operator/china-mobile/).
[58] *NB-IoT powers China Mobile smart parking*, (https://futureiot.tech/nb-iot-powers-china-mobile-smart-parking/).
[59] *Narrow Band (NB) -IoT Modem Chip Vendors*, (http://www.techplayon.com/narrow-band-nb-iot-modem-chip-vendors/).
[60] *ALT1250: CAT-M & NB-IoT Lowest Power, Smallest, Most Secured and Highly Integrated Chipset*, (https://altair-semi.com/products/alt1250/).
[61] *Quectels NB-IoT BC95 Module First to Receive GCF Certification*, (https://www.quectel.com/infocenter/news/246.htm).
[62] *Optimized Cellular IoT*, (http://riotmicro.com/products/rm1000/).
[63] *Ultra integrated chip for pure NB-IoT operation*, (http://www.sequans.com/press-release/sequans-introduces-new-nb-iot-platform-monarch-n/).
[64] *Sequans inks deal with NTT DoCoMo to boost NB-IoT development in Japan*, (https://enterpriseiotinsights.com/20180703/chipsets/sequans-inks-deal-with-ntt-docomo-to-boost-nb-iot-development-in-japan-tag23).
[65] G.A. Akpakwu, B.J. Silva, G.P. Hancke, A.M. Abu-Mahfouz, A survey on 5G networks for the internet of things: communication technologies and challenges, IEEE Access 6 (2018) 3619–3647.
[66] *What is NB-IoT? Practical tips to unlock its business potential*, (https://www.ericsson.com/en/blog/2019/10/what-is-NB-IoT).
[67] *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*, (https://www.grandviewresearch.com/industry-analysis/narrowband-nb-iot-market).
[68] *Commercial Launches*, (https://www.gsma.com/iot/mobile-iot-commercial-launches/).
[69] A.D. Zayas, P. Merino, The 3GPP NB-IoT system architecture for the internet of things, in: 2017 IEEE International Conference on Communications Workshops (ICC Workshops), IEEE, 2017, pp. 277–282.
[70] Technical Specification Group Services and System Aspects; Security aspects of Machine-Type Communications (MTC) and other mobile data applications communications enhancements, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2016. Version 13.0.1
[71] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 13.11.0
[72] R. Ratasuk, J. Tan, N. Mangalvedhe, M.H. Ng, A. Ghosh, Analysis of NB-IoT deployment in LTE guard-band, in: Vehicular Technology Conference (VTC Spring), 2017 IEEE 85th, IEEE, 2017, pp. 1–5.
[73] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 13.8.0
[74] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 13.10.0
[75] R. Ratasuk, N. Mangalvedhe, J. Kaikkonen, M. Robert, Data channel design and performance for LTE narrowband IoT, in: Vehicular Technology Conference (VTC–Fall), 2016 IEEE 84th, IEEE, 2016, pp. 1–5.
[76] S. Ha, H. Seo, Y. Moon, D. Lee, J. Jeong, A novel solution for NB-IoT cell coverage expansion, in: 2018 Global Internet of Things Summit (GIoTS), IEEE, 2018, pp. 1–5.
[77] Y.-P.E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, H.S. Razaghi, A primer on 3GPP narrowband internet of things, IEEE Commun. Mag. 55 (3) (2017) 117–123.
[78] C. Yu, L. Yu, Y. Wu, Y. He, Q. Lu, Uplink scheduling and link adaptation for narrowband internet of things systems, IEEE Access 5 (2017) 1724–1734.
[79] L. Lei, H. Xu, X. Xiong, K. Zheng, W. Xiang, Joint computation offloading and multi-user scheduling using approximate dynamic programming in NB-Iot edge computing system, IEEE Internet Things J. (2019).
[80] Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control (RLC) protocol specification, Technical Specification, 3rd Generation Partnership Project (3GPP), 2016.
[81] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Packet Data Convergence Protocol (PDCP) specification, Technical Specification, 3rd Generation Partnership Project (3GPP), 2016.
[82] S. Barros, J. Bazzo, O. dos Reis Pereira, D. Carrillo, J. Seki, Evolution of long term narrowband-IoT, in: 2017 IEEE XXIV International Conference on Electronics, Electrical Engineering and Computing (INTERCON), IEEE, 2017, pp. 1–4.
[83] J. Gozalvez, New 3GPP standard for IoT [mobile radio], IEEE Veh. Technol. Mag. 11 (1) (2016) 14–20.
[84] M. El Soussi, P. Zand, F. Pasveer, G. Dolmans, Evaluating the performance of eMTC and NB-IoT for smart city applications, in: 2018 IEEE International Conference on Communications (ICC), IEEE, 2018, pp. 1–7.
[85] B. Martinez, F. Adelantado, A. Bartoli, X. Vilajosana, Exploring the performance boundaries of NB-IoT, IEEE Internet Things J. (2019).
[86] Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 14.8.0
[87] A. Hoglund, X. Lin, O. Liberg, A. Behravan, E.A. Yavuz, M. Van Der Zee, Y. Sui, T. Tirronen, A. Ratilainen, D. Eriksson, Overview of 3GPP release 14 enhanced NB-IoT, IEEE Netw. 31 (6) (2017) 16–22.
[88] Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP), Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 14.7.0
[89] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 14.8.0
[90] X. Lin, J. Bergman, F. Gunnarsson, O. Liberg, S.M. Razavi, H.S. Razaghi, H. Rydn, Y. Sui, Positioning for the internet of things: a 3GPP perspective, IEEE Commun. Mag. 55 (12) (2017) 179–185.
[91] K. Radnosrati, G. Hendeby, C. Fritsche, F. Gunnarsson, F. Gustafsson, Performance of OTDOA positioning in narrowband IoT systems, in: Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on, IEEE, 2017, pp. 1–7.
[92] S. Hu, X. Li, F. Rusek, On time-of-arrival estimation in NB-IoT systems, in: 2019 IEEE Wireless Communications and Networking Conference (WCNC), IEEE, 2019, pp. 1–6.
[93] S. Hu, A. Berg, X. Li, F. Rusek, Improving the performance of OTDOA based positioning in NB-IoT systems (2017) 1–7.
[94] F. Tong, Y. Sun, S. He, On positioning performance for the narrow-band internet of things: how participating eNBs impact? IEEE Trans. Ind. Inf. 15 (1) (2019) 423–433.
[95] J.A. del Peral-Rosado, J.A. López-Salcedo, G. Seco-Granados, Impact of frequency-hopping NB-IoT positioning in 4G and future 5G networks, in: Communications Workshops (ICC Workshops), 2017 IEEE International Conference on, IEEE, 2017, pp. 815–820.
[96] Q. Song, S. Guo, X. Liu, Y. Yang, CSI amplitude fingerprinting-based NB-IoT indoor localization, IEEE Internet Things J. 5 (3) (2018) 1494–1504.
[97] L. Feltrin, G. Tsoukaneri, M. Condoluci, C. Buratti, T. Mahmoodi, M. Dohler, R. Verdone, Narrowband-IoT: a survey on downlink and uplink perspectives, IEEE Wireless Commun. Netw. (2018).
[98] Introduction of the Multimedia Broadcast/Multicast Service (MBMS) in the Radio Access Network (RAN); Stage 2, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018.
[99] G. Tsoukaneri, M. Condoluci, T. Mahmoodi, M. Dohler, M.K. Marina, Group communications in narrowband-IoT: architecture, procedures, and evaluation, IEEE Internet Things J. 5 (3) (2018) 1539–1549.
[100] Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 14.9.0
[101] R. Ratasuk, N. Mangalvedhe, Z. Xiong, M. Robert, D. Bhatoolaul, Enhancements of narrowband IoT in 3GPP Rel-14 and Rel-15, in: 2017 IEEE Conference on Standards for Communications and Networking (CSCN), IEEE, 2017, pp. 60–65.
[102] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Technical Specification (TS), 3rd Generation Partnership Project (3GPP), 2018. Version 15.3.0
[103] A. Hoglund, D.P. Van, T. Tirronen, O. Liberg, Y. Sui, E.A. Yavuz, 3GPP Release 15 early data transmission, IEEE Commun. Standards Mag. 2 (2) (2018) 90–96.
[104] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification, Technical Specification, 3rd Generation Partnership Project (3GPP), 2018.
[105] M. Abbasi, NB-IoT small cell: a 3GPP perspective, arXiv Preprint arXiv:1910.00677 (2019).
[106] New WID on Rel-16 enhancements for NB-IoT, Work Item Description-, 3rd Generation Partnership Project (3GPP), 2018.
[107] A. Adhikary, X. Lin, Y.-P.E. Wang, Performance evaluation of NB-IoT coverage, in: Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th, IEEE, 2016, pp. 1–5.

[108] P. Andres-Maldonado, P. Ameigeiras, J. Prados-Garzon, J.J. Ramos-Munoz, J. Navarro-Ortiz, J.M. Lopez-Soler, Analytic analysis of narrowband IoT coverage enhancement approaches, in: 2018 Global Internet of Things Summit (GIoTS), IEEE, 2018, pp. 1–6.
[109] S. Ravi, P. Zand, M. El Soussi, M. Nabi, Evaluation, modeling and optimization of coverage enhancement methods of NB-IoT, in: 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), IEEE, 2019, pp. 1–7.
[110] M. Lauridsen, H. Nguyen, B. Vejlgaard, I.Z. Kovács, P. Mogensen, M. Sorensen, Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km^2 area, in: Vehicular Technology Conference (VTC Spring), 2017 IEEE 85th, IEEE, 2017, pp. 1–5.
[111] I.Z. Kovács, P. Mogensen, M. Lauridsen, T. Jacobsen, K. Bakowski, P. Larsen, N. Mangalvedhe, R. Ratasuk, LTE IoT link budget and coverage performance in practical deployments, in: Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on, IEEE, 2017, pp. 1–6.
[112] M. Chafii, F. Bader, J. Palicot, Enhancing coverage in narrow band-IoT using machine learning, in: Wireless Communications and Networking Conference (WCNC), 2018 IEEE, IEEE, 2018, pp. 1–6.
[113] L.-S. Chen, W.-H. Chung, Y. Chen, S.-Y. Kuo, Adaptive repetition scheme with machine learning for 3GPP NB-IoT, in: 2018 IEEE 23rd Pacific Rim International Symposium on Dependable Computing (PRDC), IEEE, 2018, pp. 252–256.
[114] X. Deng, Z. Tang, L. Yi, L.T. Yang, Healing multimodal confident information coverage holes in NB-IoT-enabled networks, IEEE Internet Things J. 5 (3) (2018) 1463–1473.
[115] J.-M. Liang, K.-R. Wu, J.-J. Chen, P.-Y. Liu, Y.-C. Tseng, Energy-efficient uplink resource units scheduling for ultra-reliable communications in NB-IoT networks, Wirel. Commun. Mobile Comput. 2018 (2018).
[116] J. Lee, J. Lee, Prediction-based energy saving mechanism in 3GPP NB-IoT networks, Sensors 17 (9) (2017) 2008.
[117] A. Azari, G. Miao, C. Stefanovic, P. Popovski, Latency-energy tradeoff based on channel scheduling and repetitions in NB-IoT systems (2018) 1–7.
[118] H. Bello, X. Jian, Y. Wei, M. Chen, Energy-delay evaluation and optimization for NB-IoT PSM with periodic uplink reporting, IEEE Access (2018).
[119] P. Andres-Maldonado, M. Lauridsen, P. Ameigeiras, J.M. Lopez-Soler, Analytical modeling and experimental validation of NB-IoT device energy consumption, IEEE Internet Things J. (2019).
[120] S. Zhu, W. Wu, L. Feng, P. Zhao, F. Zhou, P. Yu, W. Li, Energy-efficient joint power control and resource allocation for cluster-based NB-IoT cellular networks, Trans. Emerg. Telecommun.Technol. 30 (4) (2019) e3266.
[121] S. Xu, Y. Liu, W. Zhang, Grouping-based discontinuous reception for massive narrowband internet of things systems, IEEE Internet Things J. 5 (3) (2018) 1561–1571.
[122] X. Yang, X. Wang, Y. Wu, L.P. Qian, W. Lu, H. Zhou, Small-cell assisted secure traffic offloading for narrowband internet of thing (NB-IoT) systems, IEEE Internet Things J. 5 (3) (2018) 1516–1526.
[123] A. Gunturu, A.K.R. Chavva, Opportunistic early decoding for NB-IoT devices using link abstraction based on RBIR metric, in: Wireless Communications and Networking Conference (WCNC), 2018 IEEE, IEEE, 2018, pp. 1–6.
[124] A.K. Sultania, P. Zand, C. Blondia, J. Famaey, Energy modeling and evaluation of NB-IoT with PSM and eDRX (2018) 1–7.
[125] S.-M. Oh, K.-R. Jung, M. Bae, J. Shin, Performance analysis for the battery consumption of the 3GPP NB-IoT device, in: Information and Communication Technology Convergence (ICTC), 2017 International Conference on, IEEE, 2017, pp. 981–983.
[126] H. Kroll, M. Korb, B. Weber, S. Willi, Q. Huang, Maximum-likelihood detection for energy-efficient timing acquisition in NB-IoT, in: Wireless Communications and Networking Conference Workshops (WCNCW), 2017 IEEE, IEEE, 2017, pp. 1–5.
[127] S.K. Goudos, M. Deruyck, D. Plets, L. Martens, W. Joseph, A novel design approach for NB-IoT networks using hybrid teaching-learning optimization (2018).
[128] X. Lin, A. Adhikary, Y.-P.E. Wang, Random access preamble design and detection for 3GPP narrowband IoT systems., IEEE Wireless Commun. Letters 5 (6) (2016) 640–643.
[129] S. Cho, H. Kim, G. Jo, Determination of optimum threshold values for nprach preamble detection in NB-IoT systems, in: 2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN), IEEE, 2018, pp. 616–618.
[130] J.-K. Hwang, C.-F. Li, C. Ma, Efficient detection and synchronization of superimposed NB-IoT NPRACH preambles, IEEE Internet Things J. 6 (1) (2018) 1173–1182.
[131] T. Li, J. Yuan, M. Torlak, Network throughput optimization for random access narrowband cognitive radio internet of things (NB-CR-IoT), IEEE Internet Things J. 5 (3) (2018) 1436–1448.
[132] T. Kim, D.M. Kim, N. Pratas, P. Popovski, D.K. Sung, An enhanced access reservation protocol with a partial preamble transmission mechanism in NB-IoT systems, IEEE Commun. Lett. 21 (10) (2017) 2270–2273.
[133] N. Jiang, Y. Deng, M. Condoluci, W. Guo, A. Nallanathan, M. Dohler, RACH Preamble repetition in NB-IoT network, IEEE Commun. Lett. 22 (6) (2018) 1244–1247.
[134] R. Harwahyu, R.-G. Cheng, W.-J. Tsai, J.-K. Hwang, G. Bianchi, Repetitions vs retransmissions: trade-off in configuring NB-IoT random access channels, IEEE Internet Things J. (2019).
[135] Y. Kim, K. Moon, T.-J. Lee, Enhanced random access method with a coverage level and subcarrier spacing in NB-IoT systems, in: Proceedings of the 2017 International Conference on Information Technology, ACM, 2017, pp. 292–296.
[136] Y. Zhao, K. Liu, H. Yan, L. Huang, A classification back-off method for capacity optimization in NB-IOT random access, in: Anti-counterfeiting, Security, and Identification (ASID), 2017 11th IEEE International Conference on, IEEE, 2017, pp. 104–108.
[137] R. Harwahyu, R.-G. Cheng, C.-H. Wei, Investigating the performance of the random access channel in NB-IoT, in: Vehicular Technology Conference (VTC-Fall), 2017 IEEE 86th, IEEE, 2017, pp. 1–5.
[138] R. Harwahyu, R.-G. Cheng, C.-H. Wei, R.F. Sari, Optimization of random access channel in NB-Iot, IEEE Internet Things J. 5 (1) (2018) 391–402.
[139] W.S. Jeon, S.B. Seo, D.G. Jeong, Effective frequency hopping pattern for ToA estimation in NB-IoT random access, IEEE Trans. Veh. Technol. (2018).
[140] Y. Sun, F. Tong, Z. Zhang, S. He, Throughput modeling and analysis of random access in narrowband internet of things, IEEE Internet Things J. 5 (3) (2018) 1485–1493.
[141] S. Cluzel, L. Franck, J. Radzik, S. Cazalens, M. Dervin, C. Baudoin, D. Dragomirescu, 3GPP NB-IoT coverage extension using LEO satellites, in: 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), IEEE, 2018, pp. 1–5.
[142] J.-B. Doré, V. Berg, TURBO-FSK: a 5G NB-IoT evolution for leo satellite networks, in: 2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP), IEEE, 2018, pp. 1040–1044.
[143] H. Malik, S.Z. Khan, J.L.R. Sarmiento, A. Kuusik, M.M. Alam, Y. Le Moullec, S. Pärand, NB-IoT network field trial: Indoor, outdoor and underground coverage campaign (2019) 537–542.
[144] T.A. Nguyen, P. Martins, T.M.T. Nguyen, et al., A new analytical model for the performance evaluation of the uplink transmission in NB-IoT networks, in: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), IEEE, 2019, pp. 1–5.
[145] D. Di Lecce, A. Grassi, G. Piro, G. Boggia, Boosting energy efficiency of NB-IoT cellular networks through cooperative relaying, in: 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), IEEE, 2018, pp. 1–5.
[146] S.-M. Oh, J. Shin, An efficient small data transmission scheme in the 3GPP NB-Iot system, IEEE Commun. Lett. 21 (3) (2017) 660–663.
[147] Y.-J. Yu, S.-C. Tseng, Downlink scheduling for narrowband internet of things (NB-IoT) systems, in: 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), IEEE, 2018, pp. 1–5.
[148] A.E. Mostafa, Y. Zhou, V.W. Wong, Connectivity maximization for narrowband IoT systems with NOMA, in: Communications (ICC), 2017 IEEE International Conference on, IEEE, 2017, pp. 1–6.
[149] T. Xu, I. Darwazeh, Non-orthogonal narrowband internet of things: adesign for saving bandwidth and doubling the number of connected devices, IEEE Internet Things J. 5 (3) (2018) 2120–2129.
[150] W. Chen, H. Zhang, H. Ji, X. Li, Dynamic QoS-aware resource allocation for narrow band internet of things, in: 2018 IEEE/CIC International Conference on Communications in China (ICCC Workshops), IEEE, 2018, pp. 107–111.
[151] A. Tusha, S. Doğan, H. Arslan, IQI mitigation for narrowband IoT systems with OFDM-IM, IEEE Access 6 (2018) 44626–44634.
[152] R. Boisguene, S.-C. Tseng, C.-W. Huang, P. Lin, A survey on NB-IoT downlink scheduling: issues and potential solutions, in: Wireless Communications and Mobile Computing Conference (IWCMC), 2017 13th International, IEEE, 2017, pp. 547–551.
[153] Y. Shi, W. Xi, H. Zhou, Efficient paging message design based on binary tree in NB-IoT system, in: Standards for Communications and Networking (CSCN), 2016 IEEE Conference on, IEEE, 2016, pp. 1–6.
[154] J. Liu, Q. Mu, L. Liu, L. Chen, Investigation about the paging resource allocation in NB-IoT, in: Wireless Personal Multimedia Communications (WPMC), 2017 20th International Symposium on, IEEE, 2017, pp. 320–324.
[155] H. Chung, S. Lee, J. Jeong, NB-IoT optimization on paging MCS and coverage level, in: 2018 15th International Symposium on Wireless Communication Systems (ISWCS), IEEE, 2018, pp. 1–5.
[156] H. Malik, H. Pervaiz, M.M. Alam, Y. Le Moullec, A. Kuusik, M.A. Imran, Radio resource management scheme in NB-IoT systems, IEEE Access 6 (2018) 15051–15064.
[157] R.C.J. Neto, E.B. Rodrigues, C.T. de Oliveira, Performance analysis of resource unit configurations for M2M traffic in the narrowband-IoT system, in: Proc. 35th Brazilian Commun. Signal Process. Symp, 2017, pp. 816–820.
[158] N. Jiang, Y. Deng, A. Nallanathan, J.A. Chambers, Reinforcement learning for real-time optimization in NB-Iot networks, IEEE J. Sel. Areas Commun. (2019).
[159] B.-Z. Hsieh, Y.-H. Chao, R.-G. Cheng, N. Nikaein, Design of a UE-specific uplink scheduler for narrowband internet-of-things (NB-IoT) systems, in: The 3rd International Conference on Intelligent Green Building and Smart Grid (IGBSG 2018), YiLan, Taiwan, 2018.
[160] V. Begishev, V. Petrov, A. Samuylov, D. Moltchanov, S. Andreev, Y. Koucheryavy, K. Samouylov, Resource allocation and sharing for heterogeneous data collection over conventional 3GPP LTE and emerging NB-Iottechnologies, Comput. Commun. 120 (2018) 93–101.
[161] N. Mangalvedhe, R. Ratasuk, A. Ghosh, NB-IoT deployment study for low power wide area cellular IoT, in: Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016 IEEE 27th Annual International Symposium on, IEEE, 2016, pp. 1–6.
[162] H. Kim, S. Cho, J. Oh, G. Jo, Uplink scheduling technique for the LTE system to improve the performance of the NB-IoT system, in: 2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN), IEEE, 2018, pp. 613–615.
[163] L. Zhang, A. Ijaz, P. Xiao, R. Tafazolli, Channel equalization and interference analysis for uplink narrowband internet of things (NB-Iot), IEEE Commun. Lett. 99 (2017) 1.
[164] J. Oh, H. Song, Study on the effect of LTE on the coexistence of NB-IoT, in: 2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN), IEEE, 2018, pp. 610–612.

[165] H. Kim, S. Cho, J. Oh, G. Jo, Analysis of LTE and NB-IoT coexistence, in: Information and Communication Technology Convergence (ICTC), 2017 International Conference on, IEEE, 2017, pp. 870–872.
[166] S. Liu, F. Yang, J. Song, Z. Han, Block sparse bayesian learning-based NB-IoT interference elimination in LTE-advanced systems, IEEE Trans. Commun. 65 (10) (2017) 4559–4571.
[167] S. Liu, L. Xiao, Z. Han, Y. Tang, Eliminating NB-IoT interference to LTE system: a sparse machine learning based approach, IEEE Internet Things J. (2019).
[168] G.J. Gonzalez, F.H. Gregorio, J. Cousseau, Interference analysis in the LTE and NB-IoT uplink multiple access with RF impairments, in: 2018 IEEE 23rd International Conference on Digital Signal Processing (DSP), IEEE, 2018, pp. 1–4.
[169] C.-Y. Chen, A.C.-S. Huang, S.-Y. Huang, J.-Y. Chen, Energy-saving scheduling in the 3GPP narrowband internet of things (NB-IoT) using energy-aware machine-to-machine relays, in: Wireless and Optical Communication Conference (WOCC), 2018 27th, IEEE, 2018, pp. 1–3.
[170] V. Petrov, A. Samuylov, V. Begishev, D. Moltchanov, S. Andreev, K. Samouylov, Y. Koucheryavy, Vehicle-based relay assistance for opportunistic crowdsensing over narrowband IoT (NB-Iot), IEEE Internet Things J. (2017).
[171] Y. Li, K. Chi, H. Chen, Z. Wang, Y. Zhu, Narrowband internet of things systems with opportunistic D2D communication, IEEE Internet Things J. 5 (3) (2018) 1474–1484.
[172] L. Militano, A. Orsino, G. Araniti, A. Iera, NB-IoT for D2D-enhanced content uploading with social trustworthiness in 5G systems, Future Internet 9 (3) (2017) 31.
[173] X. Zhang, M. Zhang, F. Meng, Y. Qiao, S. Xu, S. Hour, A low-power wide-area network information monitoring system by combining NB-IoT and LoRa, IEEE Internet Things J. 6 (1) (2019) 590–598.
[174] L. Anxin, L. Yang, C. Xiaohang, J. Huiling, Non-orthogonal multiple access (NOMA) for future downlink radio access of 5G, China Commun. 12 (Supplement) (2015) 28–37.
[175] S.R. Islam, N. Avazov, O.A. Dobre, K.-S. Kwak, Power-domain non-orthogonal multiple access (noma) in 5g systems: potentials and challenges, IEEE Commun. Surv. Tutor. 19 (2) (2017) 721–742.
[176] T. Yunzheng, L. Long, L. Shang, Z. Zhi, A survey: several technologies of non-orthogonal transmission for 5G, China Commun. 12 (10) (2015) 1–15.
[177] B. Wang, K. Wang, Z. Lu, T. Xie, J. Quan, Comparison study of non-orthogonal multiple access schemes for 5G, in: Broadband Multimedia Systems and Broadcasting (BMSB), 2015 IEEE International Symposium on, IEEE, 2015, pp. 1–5.
[178] M. Shirvanimoghaddam, M. Dohler, S.J. Johnson, Massive non-orthogonal multiple access for cellular IoT: potentials and limitations, IEEE Commun. Mag. 55 (9) (2017) 55–61.
[179] Technical Specification Group Radio Access Network; Study on Non-Orthogonal Multiple Access (NOMA) for NR, Technical Report, 3rd Generation Partnership Project (3GPP), 2018.
[180] L.P. Qian, A. Feng, Y. Huang, Y. Wu, B. Ji, Z. Shi, Optimal SIC ordering and computation resource allocation in MEC-aware NOMA NB-Iot networks, IEEE Internet Things J. (2018).
[181] D. Zhai, R. Zhang, L. Cai, B. Li, Y. Jiang, Energy-efficient user scheduling and power allocation for NOMA based wireless networks with massive IoT devices, IEEE Internet Things J. (2018).
[182] M. Shirvanimoghaddam, M. Condoluci, M. Dohler, S.J. Johnson, On the fundamental limits of random non-orthogonal multiple access in cellular massive IoT, IEEE J. Sel. Areas Commun. 35 (10) (2017) 2238–2252.
[183] A. Shahini, N. Ansari, NOMA aided narrowband IoT for machine type communications with user clustering, IEEE Internet Things J. (2019).
[184] T. Xu, C. Masouros, I. Darwazeh, Waveform and space precoding for next generation downlink narrowband IoT, IEEE Internet Things J. (2019).
[185] L. Militano, A. Orsino, G. Araniti, M. Nitti, L. Atzori, A. Iera, Trusted D2D-based data uploading in-band narrowband-IoT with social awareness, in: Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016 IEEE 27th Annual International Symposium on, IEEE, 2016, pp. 1–6.
[186] Z. Ning, X. Wang, X. Kong, W. Hou, A social-aware group formation framework for information diffusion in narrowband internet of things, IEEE Internet Things J. 5 (3) (2018) 1527–1538.
[187] Y. Miao, Y. Tian, J. Cheng, M.S. Hossain, A. Ghoneim, RADB: random access with differentiated barring for latency-constrained applications in NB-IoT network, Wirel. Commun. Mobile Comput. 2018 (2018).
[188] P. Salva-Garcia, J.M. Alcaraz-Calero, Q. Wang, J.B. Bernabe, A. Skarmeta, 5G NB-IoT: efficient network traffic filtering for multitenant IoT cellular networks, Secur. Commun. Netw. 2018 (2018).
[189] N. Javaid, A. Sher, H. Nasir, N. Guizani, Intelligence in IoT-based 5G networks: opportunities and challenges, IEEE Commun. Mag. 56 (10) (2018) 94–100.
[190] S. Narayanan, D. Tsolkas, N. Passas, L. Merakos, NB-IoT: a candidate technology for massive IoT in the 5G era, in: 2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), IEEE, 2018, pp. 1–6.
[191] J. Cao, P. Yu, M. Ma, W. Gao, Fast authentication and data transfer scheme for massive NB-IoT devices in 3GPP 5G network, IEEE Internet Things J. (2018).
[192] H. Malik, J.L.R. Sarmiento, M.M. Alam, M.A. Imran, Narrowband-internet of things (NB-IoT): performance evaluation in 5G heterogeneous wireless networks (Preprint August 2019).
[193] S. Stepanov, M. Stepanov, A. Tsogbadrakh, J. Ndayikunda, U. Andrabi, Resource allocation and sharing for transmission of batched NB-IoT traffic over 3GPP LTE, in: 2019 24th Conference of Open Innovations Association (FRUCT), IEEE, 2019, pp. 422–429.
[194] M. Shafi, A.F. Molisch, P.J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, G. Wunder, 5G: a tutorial overview of standards, trials, challenges, deployment, and practice, IEEE J. Sel. Areas Commun. 35 (6) (2017) 1201–1221.
[195] M. Nitti, R. Girau, L. Atzori, Trustworthiness management in the social internet of things, IEEE Trans. Knowl. Data Eng. 26 (5) (2014) 1253–1266.
[196] M. Agiwal, A. Roy, N. Saxena, Next generation 5G wireless networks: acomprehensive survey, IEEE Commun. Surv. Tutor. 18 (3) (2016) 1617–1655.
[197] I. Qualcomm Technologies, Accelerating the mobile ecosystem expansion in the 5G era with LTE advanced pro (2018).
[198] M.R. Palattella, M. Dohler, A. Grieco, G. Rizzo, J. Torsner, T. Engel, L. Ladid, Internet of things in the 5G era: enablers, architecture, and business models, IEEE J. Sel. Areas Commun. 34 (3) (2016) 510–527.
[199] E. Luján, J.A.Z. Mellino, A.D. Otero, L.R. Vega, C.G. Galarza, E.E. Mocskos, IEEE Internet Things J. (2019).
[200] *LTE-M and NB-IoT meet the 5G performance requirements*, (https://www.ericsson.com/en/blog/2018/12/lte-m-and-nb-iot-meet-the-5g-performance-requirements).
[201] J. Cheng, W. Chen, F. Tao, C.-L. Lin, Industrial iot in 5g environment towards smart manufacturing, J. Ind. Inf. Integr. 10 (2018) 10–19.
[202] Further views on Rel-17 NR Light work area, Technical Report, 3rd Generation Partnership Project (3GPP), 2019.
[203] H. Zhang, J. Li, B. Wen, Y. Xun, J. Liu, Connecting intelligent things in smart hospitals using NB-Iot, IEEE Internet Things J. (2018).
[204] S.K. Routray, S. Anand, Narrowband IoT for healthcare, in: 2017 International Conference on Information Communication and Embedded Systems (ICICES), IEEE, 2017, pp. 1–4.
[205] S. Anand, S.K. Routray, Issues and challenges in healthcare narrowband IoT, in: Inventive Communication and Computational Technologies (ICICCT), 2017 International Conference on, IEEE, 2017, pp. 486–489.
[206] T. Lin, H. Rivano, F. Le Mouël, A survey of smart parking solutions, IEEE Trans. Intell. Transp. Syst. 18 (12) (2017) 3229–3253.
[207] J. Shi, L. Jin, J. Li, Z. Fang, A smart parking system based on NB-IoT and third-party payment platform, in: Communications and Information Technologies (ISCIT), 2017 17th International Symposium on, IEEE, 2017, pp. 1–5.
[208] W. Zhai, Design of narrowband-IoT oriented wireless sensor network in urban smart parking, Int. J. Online Eng. (iJOE) 13 (12) (2017) 116–126.
[209] A. Athanase, F. Tossa, T.O.D. Edoh, W. Abdou, M.K. Assogba, E. Ezin, A.C. Vianou, Performance analysis of NB-IOT network for patients monitoring in rural areas (irehi2018) (2019).
[210] L. Zhao, Q. Gao, R. Wang, N. Fang, Z. Jin, N. Wan, L. Xu, Intelligent street light system based on NB-IoT and energy-saving algorithm, in: 2018 3rd International Conference on Smart and Sustainable Technologies (SpliTech), IEEE, 2018, pp. 1–6.
[211] Y. Liu, Z. Ge, G. Lv, S. Wang, Research on automatic garbage detection system based on deep learning and narrowband internet of things, in: Journal of Physics: Conference Series, 1069, IOP Publishing, 2018, p. 012032.
[212] Y. Zhu, G. Jia, G. Han, Z. Zhou, M. Guizani, An NB-IoT-based smart trash can system for improved health in smart cities, in: 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), IEEE, 2019, pp. 763–768.
[213] X. Cao, Y. Li, Data collection and network architecture analysis in internet of vehicles based on NB-IoT, in: 2018 International Conference on Intelligent Transportation, Big Data & Smart City (ICITBS), IEEE, 2018, pp. 157–160.
[214] D. Vasisht, Z. Kapetanovic, J. Won, X. Jin, R. Chandra, S.N. Sinha, A. Kapoor, M. Sudarshan, S. Stratman, Farmbeats: an IoT platform for data-driven agriculture, in: NSDI, 2017, pp. 515–529.
[215] H. Joe, H. An, W. Wang, W. Lee, H. Park, In-band cellular IoT for smart home applications, in: Consumer Electronics (ICCE), 2017 IEEE International Conference on, IEEE, 2017, pp. 336–337.
[216] M. Pennacchioni, M.-G. Di Benedette, T. Pecorella, C. Carlini, P. Obino, NB-IoT system deployment for smart metering: evaluation of coverage and capacity performances, in: AEIT International Annual Conference, 2017, IEEE, 2017, pp. 1–6.
[217] H. Ji, L. Miao, J. Dong, Indoor environment remote monitoring system based on NB-IoT, in: IOP Conference Series: Materials Science and Engineering, 452, IOP Publishing, 2018, p. 022162.
[218] S. Anand, R. Regi, Remote monitoring of water level in industrial storage tanks using NB-IoT, in: 2018 International Conference on Communication information and Computing Technology (ICCICT), IEEE, 2018, pp. 1–4.
[219] R. Nordin, H. Mohamad, M. Behjati, A.H. Kelechi, N. Ramli, K. Ishizu, F. Kojima, M. Ismail, M. Idris, The world-first deployment of narrowband iot for rural hydrological monitoring in UNESCO biosphere environment, in: Smart Instrumentation, Measurement and Application (ICSIMA), 2017 IEEE 4th International Conference on, IEEE, 2017, pp. 1–5.
[220] S. Duangsuwan, A. Takarn, R. Nujankaew, P. Jamjareegulgarn, A study of air pollution smart sensors LPWAN via NB-IoT for thailand smart cities 4.0, in: 2018 10th International Conference on Knowledge and Smart Technology (KST), IEEE, 2018, pp. 206–209.
[221] S. Duangsuwan, A. Takarn, P. Jamjareegulgarn, A development on air pollution detection sensors based on NB-IoT network for smart cities, in: 2018 18th International Symposium on Communications and Information Technologies (ISCIT), IEEE, 2018, pp. 313–317.
[222] Y. Li, X. Cheng, Y. Cao, D. Wang, L. Yang, Smart choice for the smart grid: narrowband internet of things (NB-IoT), IEEE Internet Things J. 5 (3) (2018) 1505–1515.
[223] V. Nair, R. Litjens, H. Zhang, Assessment of the suitability of nb-iot technology for orm in smart grids, in: 2018 European Conference on Networks and Communications (EuCNC), IEEE, 2018, pp. 418–423.

[224] S. Persia, L. Rea, Next generation M2M cellular networks: LTE-MTC and NB-IoT capacity analysis for smart grids applications, in: AEIT International Annual Conference (AEIT), 2016, IEEE, 2016, pp. 1–6.
[225] *Samsung launches NB-IoT GPS smart tag*, 2017., (https://www.zdnet.com/article/samsung-launches-nb-iot-gps-smart-tag/).
[226] Y. Kim, T.-J. Lee, V2IoT communication systems for road safety, IEEE Wireless Commun. Lett. (2019).
[227] Remaining Issues in Early Data Transmission over NAS, Technical Report, 3rd Generation Partnership Project (3GPP), 2019.
[228] Y. Moon, S. Ha, M. Park, D. Lee, J. Jeong, A methodology of NB-IoT mobility optimization, in: 2018 Global Internet of Things Summit (GIoTS), IEEE, 2018, pp. 1–5.
[229] Y. Lin, F. Jiang, Z. Wang, Z. Wang, Research on PUF-based security enhancement of narrow-band internet of things, in: 2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA), IEEE, 2018, pp. 702–709.
[230] S. Martiradonna, A. Grassi, G. Piro, L.A. Grieco, G. Boggia, An open source platform for exploring NB-IoT system performance, in: European Wireless 2018; 24th European Wireless Conference, VDE, 2018, pp. 1–6.
[231] A. Puschmann, P. Sutton, I. Gomez, Implementing NB-Iot in software-experiences using the srslte library, arXiv Preprint arXiv:1705.03529 (2017).
[232] E. Migabo, K. Djouani, A. Kurien, A modelling approach for the narrowband iot NB-IoT physical PHY layer performance, in: IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society, IEEE, 2018, pp. 5207–5214.
[233] L. Novelli, L. Jorge, P. Melo, A. Koscianski, Application protocols and wireless communication for IoT: a simulation case study proposal, in: 2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP), IEEE, 2018, pp. 1–6.
[234] Y. Miao, W. Li, D. Tian, M.S. Hossain, M.F. Alhamid, Narrowband internet of things: simulation and modeling, IEEE Internet Things J. 5 (4) (2018) 2304–2314.

Eshita Rastogi is currently working towards her Ph.D degree from Sungkyunkwan University, South Korea. She received her M.Tech degree in communication engineering from Madan Mohan Malaviya University of Technology, India. Her research interests include NB-IoT, LPWAN, energy management in LTE wireless networks, and vehicular networks.

Navrati Saxena is an Associate Professor and director of Mobile Ubiquitous System Information Center (MUSIC) in Sungkyunkwan University (SKKU), Korea. Prior to joining SKKU, she was an Assistant Professor in Amity University India and a visiting researcher in University of Texas at Arlington, USA. She completed her Ph.D from University of Trento, Italy. Her research interests involve 5G wireless, IoT and smart grids. She serves in guest editorial and technical program committee of international journals and conferences. She has co-authored one book (Taylor & Francis) and published more than 60 international journals.

Abhishek Roy is currently working as a Senior Technical Manager in Wireless Standards Team of MediaTek USA Inc. Prior to this he worked as Principal Engineer in Network System Design Lab, Samsung Electronics, Korea. He received his Ph.D. in 2010 from Sungkyunkwan University, Korea and MS in 2002 from the University of Texas at Arlington, USA. His research interests include resource and energy management in 5G wireless, IoT, social networking and smart grids. He serves in editorial boards and technical program committee of many international journals and conferences. He has co-authored one book and published more than 60 international journals.

Dong Reyol Shin is presently a president of Sungkyunkwan University and professor in College of Software at Sungkyunkwan University, South Korea. He was a Dean of the College of Information and Communication Engineering and Sungkyun Convergence Institute. He received his Ph.D. in 1992 from Georgia Institute of Technology, USA. He completed his MS in 1982 and BS in 1980 in Electrical and Electronic Engineering from Korea Advanced Institute of Science and Technology (KAIST), South Korea and Sungkyunkwan University, South Korea, respectively. His research interests include wireless communication and networks, Ubiquitous Computing and Networking, Sensor Networks and Big Data. He is a member of IEEE, ACM, IEICE, KIEE. He serves in editorial boards in Institute of Electronics Engineers of Korea (IEEK) and Korea Information Processing Society (KIPS).