Narrowband Internet of Things: Evolutions, Technologies, and Open Issues

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***Abstract*—We are on the threshold of the explosive growth in the global Internet-of-Things (IoT) market. Comparing with the legacy human-centric applications, machine type communication scenarios exhibit totally different characteristics, such as low throughput, delay insensitivity, occasional transmission, and deep coverage. Meanwhile, it also requires the terminal devices to be cheap enough and sustain long battery life. These demands hasten the prosperity of low power wide area (LPWA) technologies. Narrowband IoT (NB-IoT) is the newest Long Term Evolution (LTE) specification ratified by the third generation partner project as one of the LPWA solutions to achieve the objectives of super coverage, low power, low cost, and massive connection. Working in the licensed frequency band, it is designed to reuse and coexist with the existing LTE cellular networks, which endows it with outstanding advantages in decreasing network installation cost and minimizing product time-to-market. In this backdrop, it has been extensively regarded as one of the most promising technologies toward the IoT landscape. However, as a new LTE standard, there are still a lot of challenges that need to overcome. This paper surveys its evolutions, technologies, and issues, spanning from performance analysis, design optimization, combination with other leading technologies, to implementation and application. The goal is to deliver a holistic understanding for the emerging wireless communication system, in helping to spur further research in accelerating the broad use of NB-IoT.**

***Index Terms*—Internet of Things (IoT), Long Term Evolution (LTE), low power wide area (LPWA), machine type communication (MTC), narrowband IoT (NB-IoT).**

I. Introduction

THE INTERNET-of-Things (IoT), whose key idea is to connect everything and everyone by Internet, has become a very hot topic in recent years [1]. Its emergence is an inevitability as the result of the advancements of the wireless communication technology. Since the 80s of last century when the first cellular phone comes into being, the telecommunication industry has experienced four generations' development. On the one hand, from the initial human-to-human (H2H) communication to the subsequent human-to-machine (H2M) communication, it is intuitive for the researchers to breed the idea of machine-to-machine (M2M) communication. On the other hand, from the business point of view, the volumes of the legacy voice services (represented by H2H) have long since touched the top ceilings; afterwards, the vigorous expansions of the 4G networks have already successfully turned the data services (represented by H2H and H2M) into the master income sources of the mobile operators and promoted them to reach a new revenue summit. Where is the next blue ocean? As far as it goes, the answer seems to be the M2M communication, supported by the diverse IoT technologies. This is a tremendous market. By 2020, it is expected that the IoT connections in the world will reach tens of billions level, far exceeding the number of concurrent personal computers and mobile phones [2]; moving forward to 2024, the overall IoT industry is expected to generate a revenue of $4.3 trillion, coming from different sectors, such as device connectivity, manufacturing, and other value added services [3]. To date, IoT is playing an important role in pushing the global economic growth, and is even possible to become the driving force initiating the fourth industrial revolution [4].

Comparing with the traditional human-centric applications that need high-speed Internet access, the characteristics of the machine type communication (MTC) [5] are totally different in terms of traffic pattern, delay sensitivity, and deployment density [6]. The typical use cases often contain a large number of mostly battery-powered devices, which rarely transmit or receive data. The main considerations of those use cases for the underlying radio technologies are low power consumption, low data rate, scalability, and big coverage [7]. Therefore, the well-known short-range wireless technologies, such as ZigBee [8], RFID [9], Wi-Fi [10], Bluetooth low energy (BLE) [11], 6LoWPAN [12], WirelessHART [13] and Z-Wave [14], become inappropriate since their communication scopes are generally within tens or hundreds of meters. In the same way, the conventional cellular network technologies, such as global system for mobile communication (2G/GSM), universal mobile telecommunications system (3G/UMTS), and Long Term Evolution (4G/LTE) suffer from

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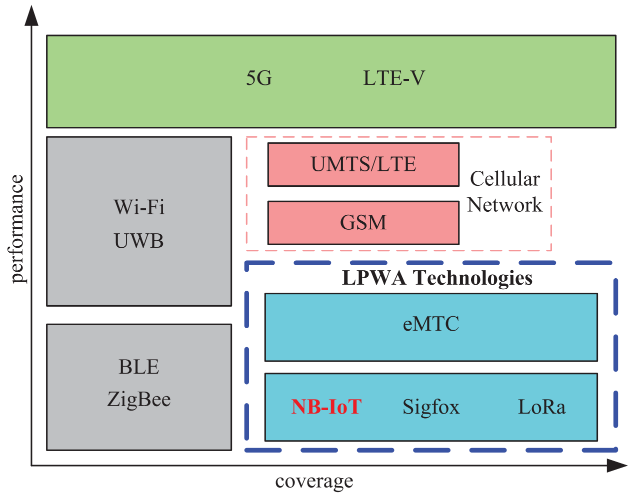

Fig. 1. Performance versus coverage for different application scenarios.

high power consumption and manufacturing cost to the user equipments (UEs) since their designs, originally orienting to the high speed data rate applications, are rather complicated. In contrast, low power wide area (LPWA) networks are perfectly suitable for the IoT applications that only need to transmit tiny amounts of information in the long range [15] as shown in Fig. 1. LPWA, a generic new term for a group of technologies that enable wide area communications with lower cost nodes and better power consumption, did not even exist as recently as early 2013 [16], but rapidly attracted so much interests after Sigfox [17] and LoRa [18] hit the market. Nowadays it has proven to be one of the fastest growing spaces in the IoT landscape.

From the perspective of frequency spectrum, the LPWA technologies can be separated into two categories: the one employing unlicensed frequency band, and the other utilizing licensed frequency band. The former are also called proprietary technologies, including LoRa, Sigfox, radio phase multiple access [19], Telensa [20], Qowisio [21], etc., which operate in either subgigahertz or 2.4 GHz industrial, scientific, and medical band. They are mostly nonstandard, and implemented as user-defined, as well as constructed with star or mesh architectures. Due to the property of unlicensed spectrum, the top concerns come from the channel access collisions since the free spectrum is shared by multiple technologies. Typically, transmission time is limited within a duty cycle, and either frequency hopping or carrier sensing schemes are required to avoid interference with coexisting systems. The latter are usually based on the cellular networks, and may work in the same frequency band as 2G/GSM, 3G/UMTS, or 4G/LTE systems. They are generally proposed by the international organizations and targeted at standardization. Although the licensed LPWA technologies arise later than the prior proprietary counterparts, and some of them are seen as the responses to the competitions of Sigfox and LoRa [22], they present outstanding advantages to potentially surpass the pioneers [23]. The licensed bands do not suffer from the duty cycle limitations and the uncontrollable interference, and can benefit from higher downlink transmit power because the base station (BS, also called evolved Node B, eNB) is more powerful than the plain communication terminals. Besides, reusing the existing cellular infrastructure can not only reduce the network installation, operational and maintenance cost but also speedup the specification formulation, minimize the development effort, and decrease the product time-to-market. Moreover, the BS-centric architecture is also simpler than the complex overlay network deployment which often occurs in the proprietary technologies [24]. Again such a background, the third generation partnership project (3GPP) introduced its LPWA solution, narrowband IoT (NB-IoT), in its LTE Release 13 [25], and immediately aroused enormous attentions from both industry and academia [26].

As a new 3GPP radio-access technology, NB-IoT is not fully backward compatible with existing 3GPP devices, but it can harmoniously coexist with legacy GSM, general packet radio service (GPRS), and LTE networks [27]. To meet the requirements of LPWA, meanwhile reuse the functionalities of LTE design, the system bandwidth exploited by NB-IoT for both downlink and uplink is set to be 180 kHz, which is just the size of one physical resource block (PRB) in LTE standard. It still increases the maximum number of retransmission to enhance coverage, and utilizes the power saving mode (PSM) and the extended discontinuous reception (eDRX) techniques to lengthen battery life. According to the Release 13 specification, the current objectives of NB-IoT are designated from the following four dimensions [28].

1) *Super Coverage:* Realize the maximum coupling loss (MCL) of 164 dB while satisfying a data rate of at least 160 bps at the application layer, improving the indoor coverage by 20 dB compared to the GPRS standard.
2) *Low Power:* Maintain the device life of ten years with battery capacity of 5 Wh and uplink interval of 120 min, and keep power consumption under 15 W once entering PSM state.
3) *Low Cost:* Guarantee the devices very cheap so that they can be deployed in mass or even in disposable manner. The recommendations are $1 U.S. for the chip and $5 U.S. for the module.
4) *Massive Connections:* Support the connection of at least 52 547 low throughput devices within a cell-site sector, where the traffic model assumes 40 devices per home or 20 devices per person.

In spite of these exciting prospects exhibited by NB-IoT, there are still a series of challenges that need to overcome. Although NB-IoT reuses the majorities of the LTE principles, such as orthogonal frequency division multiplexing (OFDM) type of modulation in downlink, single carrier frequency division multiple access (SC-FDMA) in uplink, channel coding, rate matching and interleaving, etc., a host of features such as synchronization sequences, random access preamble, broadcast channel, control channel, etc., are modified to distinguish with the LTE specification [29]. These changes are motivated by the fact that the NB-IoT can only operate on a minimum bandwidth of 180 kHz (1 PRB), whereas many channels in LTE were designed to span multiple PRBs occupying greater bandwidth than 180 kHz. It causes many contributions previously proposed for LTE to be unfit for the NB-IoT

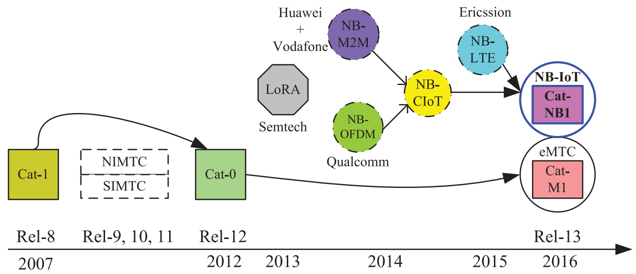

Fig. 2. NB-IoT standardization process.

TABLE I
EVOLUTIONS OF 3GPP UE CATEGORIES TOWARD MTC

	Cat-1	Cat-0	Cat-M1 (eMTC)	Cat-NB1 (NB-IoT)
Deployment	In-band LTE	In-band LTE	In-band LTE	Guard-band/ In-band LTE Stand-alone
Downlink	OFDMA [15 kHz]	OFDMA [15 kHz]	OFDMA [15 kHz]	OFDMA [15 kHz]
Uplink	SC-FDMA [15 kHz]	SC-FDMA [15 kHz]	SC-FDMA [15 kHz]	SC-FDMA [3.75/15 kHz]
Peak Rate	DL:10 Mbps UL:5 Mbps	DL:1Mbps UL:1Mbps	DL: 1 Mbps UL: 1 Mbps	DL: 20 kbps UL: 250 kbps
Bandwidth	20 MHz	20 MHz	1.4 MHz	200 kHz
Duplex	Full-Duplex	Half-Duplex	Half-Duplex	Half-Duplex
Trans. Power	23 dBm	23 dBm	23 or 20 dBm	23 dBm
Power Saving Tech.	PSM, eDRX	PSM, eDRX	PSM, eDRX	PSM, eDRX

conditions, and gives birth to a plenty of new problems. They are not only related to the deep theoretical investigation of modeling, performance evaluation, and optimization, but also involved with the concrete design and implementation concerns in real applications. For instance, according to the public reports and published papers, as the NB-IoT networks are eventually ready to rollout in the practical deployments like smart city [30], eHealth [31], smart parking [32], smart bike sharing [33], smart metering and tracking [34], the developers are wondering how much data they can exchange between sensors and platforms, how much time it will take to transfer these data, etc. [35]. This paper surveys the work done toward all of these difficulties. The goal is to develop a comprehensive understanding of the key technologies and open issues, so as to spur further research in accelerating the broad use of the NB-IoT systems.

The remainder of this paper is organized as follows. Section II retrospects the evolution of NB-IoT specification. Section III overviews the key technologies employed by NB-IoT to realize the objectives. Section IV presents the open issues, including performance analysis, design optimization, and combination with other technologies. Section V concludes this paper.

II. EVOLUTIONS OF NB-IOT

NB-IoT is a new term, but not created as a sudden thing. Although it was first proposed as the result of the 3GPP Work Item TR 45.820 in September 2015, and the corresponding standardization was frozen in June 2016, its earliest history can data back to December 2007 when the 3GPP pushed out the first LTE specifications in Release 8 [36]. Fig. 2 depicts the whole NB-IoT standardization process.

It is a good roadmap to retrospect the evolution of NB-IoT along the changes of UE categories defined by 3GPP. UE is an important concept in the 3GPP lingo, and refers to the cellular equipment used by the subscribes to access the core network, which can be a smartphone or an embedded device attached in an M2M facility. According to TS 36.306 [37], the 3GPP defines multiple categories for UE to support various hardware capabilities. They are different in terms of the maximum data rates supported by the downlink and the uplink, which are associated, for instance, with the support of multiple in multiple out (MIMO) transmission [38]. Table I summarizes the 3GPP UE categories oriented to the MTC scenarios.

In Release 8, the 3GPP introduced the initial version of LTE MTC standards, which was based on Cat-1. It had the lowest capability with maximum data rates of 10 Mb/s downlink and 5 Mb/s uplink. Comparatively, the highest category in the same Release, called Cat-5, hold bit rates of 300 Mb/s downlink and 75 Mb/s uplink. Although the Cat-1 UEs have no support of MIMO techniques, they still contain two receiver antennas and have to support all radio frequency (RF) channel bandwidth conditions from 1.4 to 20 MHz, which no doubt increases the hardware complexity and cannot meet the requirements of IoT by failing to decrease equipment cost and reduce power consumption. Furthermore, the supported communication range is also limited. As the first release for MTC applications, its focus was mainly put on the optimization of charging mechanisms, addressing, fixed location or low mobility, low activity, and handling of large numbers of subscribers as well as handling of security risks.

No significant progresses were made in Release 9, 10, and 11 except for proposing two new terms: network improvements for MTC and system improvements for MTC, which specified a group of requirements to make the network and system more suitable for MTC. Until Release 12 [39], the 3GPP introduced a new UE category Cat-0 to resolve the cost and power issues left over by Release 8. Cat-0 achieved cost reduction of about 50% compared to Cat-1. Meanwhile, in the light of TS 24.301 [40] and TS 23.682 [41], a new PSM mechanism was introduced in this Release to save energy when the device had no data to transmit or receive. It still discussed some other techniques as part of the Cat-0 specification in TS 36.888 [42] to deeply cater for the MTC demands, which include half-duplex transmission, single RF chain, reduced peak throughput, etc. However, employing narrower system bandwidth to further cut down cost and boost up coverage was postponed to the next Release.

In accordance with the normal progress, the 3GPP continues to work toward the promising IoT market on the basis of Release 12. It proposed the concept of evolved MTC (eMTC, also referred to as LTE-M) and defined a new low complexity UE category Cat-M1 (previously known as Cat-M) for Release 13. The most two obvious characteristics of Cat-M1 are restricting the system bandwidth to 1.4 MHz and enhancing the coverage range by 15 dB. Reducing bandwidth has a heavy impact on the design of receiver because it can reduce the complexity of the baseband processing, thereby achieving an additional 50% cost reduction compared to Cat-0. Enhancing coverage can allow operators to reach MTC equipments in poor coverage situations, such as meters located in basements. For the purpose of achieving more power savings and realizing ultra long battery life, Release 13 introduced eDRX through the usage of longer discontinuous reception (DRX) timers, whose idea consists in monitoring the downlink signaling during a limited period of time while keeping the device slept during the remaining time.

Nevertheless, the normative work rhythm of the 3GPP was influenced by the emergence of LoRa, which was presented in August 2013 by Semtech Corporation [43] and rapidly occupied large amount of MTC market share in many countries. As mentioned in the previous section, it was a proprietary technology and mastered by the nontraditional network device providers, which caused huge panic from the well-established network firms. Consequently, in May 2014, Huawei [44] and Vodafone [45] proposed a study item of NB-M2M to the 3GPP, which quickly acquired strong supports and extensive attentions from the other leading operators. In October of the same year, Qualcomm [46] submitted a new narrowband proposal namely NB-OFDM. In May of the next year, both technologies merged into narrowband cellular IoT (NB-CIoT). At the same time, Ericsson [47] also accelerated their research on this area and proposed narrowband LTE (NB-LTE) in August 2015. Finally, in September 2015, the 3GPP accepted the inclusion of both NB-CIoT and NB-LTE as single one Work Item and completed its standardization in Release 13.

The main divergence of NB-LTE and NB-CIoT comes down to the level of reusing the existing LTE systems. NB-LTE can be fully integrated into the concurrent LTE specifications, and work within the LTE bands without the need of an overlay network. In contrast, NB-CIoT requires new chipsets and can not be backwards compatible with any LTE standards earlier than Release 13. Ultimately, in November 2015, the 3GPP agreed these two initiatives and evolved into only one standard called NB-IoT, based on nonbackward-compatible variant of evolved universal telecommunication radio access, aiming at implementation of improved indoor coverage, massive connection of low throughput devices, low delay sensitivity, ultra low device cost, and power consumption. By far, NB-IoT has kicked off NB-CIoT and NB-LTE to become the main stream 3GPP LPWA solution. In June 2016, the 3GPP completed the NB-IoT standardization and defined a new UE category called Cat-NB1 (also known as Cat-M2), which reduced the complexity by up to 90% compared with Cat-1. At present, the Release 14 is on the way of formulation and is expected to be available in the fourth quarter of 2017.

Counting in the original eMTC (or LTE-M), which coexists with NB-IoT as part of Release 13, and the other two leading proprietary technologies LoRa and Sigfox, which have already been successfully deployed in some countries, NB-IoT is confronting severe competition as an IoT/MTC new candidate. Table II compares it with the other three LPWA competitors in terms of transmission rate, coverage range, battery life, device cost, etc. We can find out the following.

TABLE II
COMPARISONS OF NB-IOT WITH LORA, SIGFOX, AND eMTC

	NB-IoT	**LoRa**	**Sigfox**	**eMTC**
Spectrum	licensed	unlicensed	unlicensed	Licensed
Band width	200 kHz	7.8~500 kHz	200 kHz	1.4 MHz
Peak rate	160~250 kbps (DL) 160~200 kbps (UL)	290 bps ~ 50 kbps (DL/UL)	100 bps (UL) 600 bps (DL)	< 1Mbps
Battery life	~10 years	~ 10 years	8~10 years	5~10 years
Coverage	urban: ~8km suburban: ~25km	urban: ~5km suburban: ~15km	urban:~10km suburban: ~50km	urban: ~5km suburban: ~17km
Module cost	< $5	< $5	~ $10	< $10

1) eMTC has the highest speed due to the widest bandwidth, but also suffers from the highest cost, so it is only fit for the high-end applications without sensitivities to prices.
2) Sigfox has the largest coverage, but at the cost of the lowest data rate, so it can be only applied in the low-end applications with very low delay requirements.
3) Comparatively, NB-IoT and LoRa show better balance among all of the listed parameters, so they can cater for more use cases spreading from the low-end to the high-end scenarios in a variety of fields [48]. But NB-IoT can get support from the operators due to the licensed attribute. In contrast, LoRa just lacks such powerful business drivers. Especially, NB-IoT still manifests some advantages in both peak rate and coverage range, which can also aid it to win more market share in the future competitions with LoRa.

However, it must be pointed out that these results are merely looked up from their respective specifications. The actual performance will not be convictive until the real applications are deployed. Currently, with the NB-IoT commercial rollouts being in progress, it is of the essence to thoroughly present the key technologies and open issues of this topic, which can help the developers to better understand this emerging radio access technology.

III. KEY TECHNOLOGIES

In this section, we provide a state-of-the-art overview of the key technologies that help to achieve the aforementioned design objectives for NB-IoT. We also emphasize the design tradeoffs induced by them. In particular, we highlight the NB-IoT new features and their significant deviations with the legacy LTE specification.

A. Super Coverage

Extending coverage at high frequency band, especially improving 20 dB than the GPRS standard at the premise of decreasing the UE transmit power from 33 to 23 dBm, is a great challenge. In 3GPP standardization, reduced network bandwidth and soft combined retransmissions are employed as

TABLE III
COMPARISONS OF GPRS AND NB-IOT IN PSD

Standard	Power (mW)	Bandwidth (kHz)	PSD (mW/kHz)	Ratio
GPRS	2000	200	10	--
NB-IoT	200	3.75	53.33	5.33

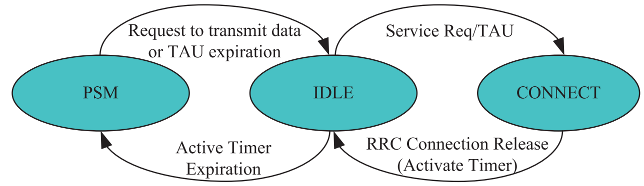

Fig. 3. State transition diagram for PSM.

two basic solutions to achieve the coverage enhancement for NB-IoT.

First, using reduced system bandwidth elevates the UE transmit power spectral density (PSD). As listed in Table III, the NB-IoT bandwidth for the uplink is only 3.75 kHz while the GPRS is 200 kHz, so their PSD ratio reaches around 5.33. If we convert it into the format of dB, $10 \times \log(5.3)$ is nearly equal to 7 dB. In other words, the reduced bandwidth can bring 7 dB gains of coverage enhancement. It is worthwhile to mention that this explanation assumes the identical frequency band used by both NB-IoT and GPRS, and is made from the uplink standpoint because the UE is more power-limited than the BS, causing the uplink more coverage-limited than the downlink. TR 45.820 also gives an illustration of how the MCL 164 dB is computed, but its object is the downlink.

Second, repeat transmission is another key technology to achieve super coverage with low complexity. There are two types of repetition mechanisms, which are also referred to as the hybrid automatic retransmission request (HARQ) schemes [49]. In HARQ type-I, each encoded data frame is retransmitted until the frame passes the cyclic redundancy check test or the maximum number of retransmissions is reached, and the erroneous frames are simply discarded. By contrast, in HARQ type-II, each retransmission can be incrementally soft combined at the receiver to raise error correction. NB-IoT employs HARQ type-II scheme, and increases the maximum repetition number by a large margin comparing with LTE, which reaches 128 for the uplink. Due to the channel estimator, a repetition by a factor of 2 results in less than 3 dB improvement in coverage performance [29], so the coverage gain for the repetition of 128 is nearly 13 dB in practice as estimated.

Putting them together, we can derive the 20 dB gains of coverage enhancement compared to the GPRS standard. It must be pointed out that reduced bandwidth degrades the data rate, and large number of retransmissions also increases the latency. These are the negative effects of the two technologies.

B. Low Power

The ultra long battery life of NB-IoT is mainly achieved through two technologies: 1) PSM introduced in Release 12 and 2) eDRX introduced in Release 13. Both of them take advantage of the low frequency of data transmission in MTC applications, and share the similar logic, i.e., lengthening the UE deep sleep time as long as possible, but they are totally independent, and are fit for different scenarios.

The principle of PSM is very simple. It adds a new PSM state as the sub state of the original IDLE state. In this state, the RF unit at the UE side is completely shut off, causing the downlink inaccessible. If there is downlink data notification that reaches the mobile mobility entity (MME) at the core network side, the MME can only notify the serving gateway to cache the user downlink data and delay the paging request; only when the UE itself has mobile originated messages to transmit, it goes back to the IDLE and subsequent CONNECT states. Fig. 3 depicts the state transition diagram. The occasion when the UE enters the PSM state and the duration time which the UE can last for at the PSM state are applied by the UE to the core network. During the process of attach or tracking area update, the UE asks for an active timer (AT). Once the UE transits from CONNECT to IDLE, the AT is activated; and when the AT expires, the UE skips into PSM. The maximum PSM duration time in NB-IoT is 310 h, which is long enough to ensure the tremendous power savings. However, the drawback is to sacrifice the response time for the mobile terminated (MT) messages; therefore, it can only be used for the applications with relaxed real-time requirements, such as smart metering.

To mitigate the no-response problem for the MT messages caused by PSM, the 3GPP introduced eDRX in Release 13 as the supplement of the low power solutions. It is an evolution of the DRX technique that works at the IDLE or CONNECT states, and the main idea is to increase the paging monitoring interval for avoiding the unnecessary power consumptions. The basic principles of DRX are twofold: first, designing a precise timer to strictly synchronize the UE and the core network; second, designing an efficient communication mechanism that is convenient for the negotiations of the UE and the core network about whether and when the UE can go dormant. In this way, the UE only needs to monitor the paging frame at the prescribed paging occasion (PO) to check whether there is paging-radio network temporary identity on the physical downlink control channel (PDCCH). If positive, the UE starts to receive the data from the physical download shared channel (PDSCH) according to the parameters indicated by the PDCCH; otherwise, the UE starts to sleep until the arrival of the next PO. For NB-IoT, the PO interval can be set up to 2.92 h from the traditional 2.56 s in the legacy LTE system for adapting to the much lower downlink data transmission frequency of the MTC applications. Fig. 4 describes the modification of eDRX compared to DRX. Albeit inferior to PSM in energy savings because of the extra PO monitoring, eDRX can effectively improves the downlink accessibility, so it can apply in the scenarios, such as connected health or object tracking [50].

According to the TR 45.820, if both PSM and eDRX are employed, and the UE transmits a packet message of 200

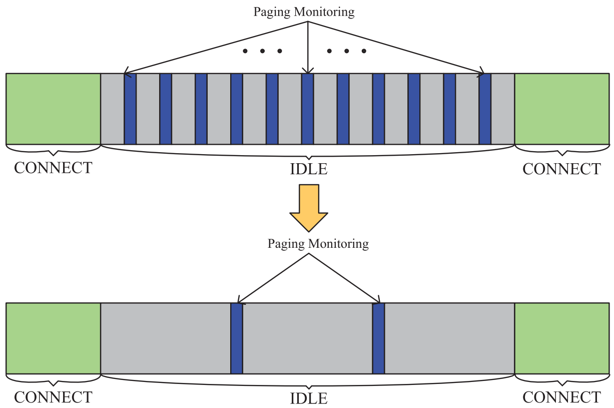

Fig. 4. Modification of eDRX compared to DRX.

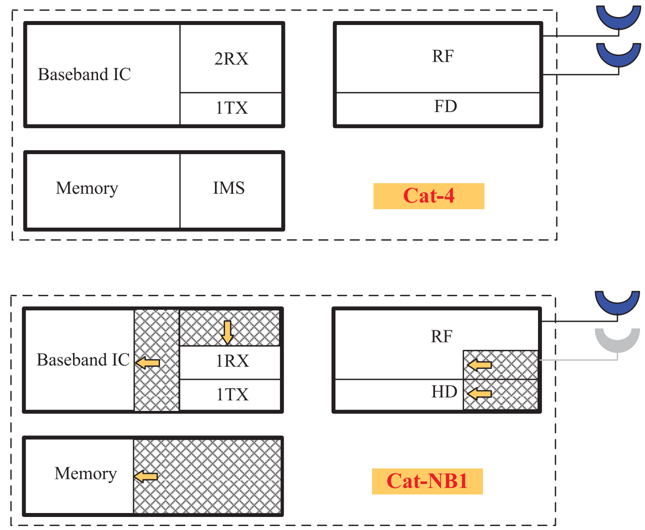

Fig. 5. Chip area reduction of Cat-NB1 compared to Cat-4.

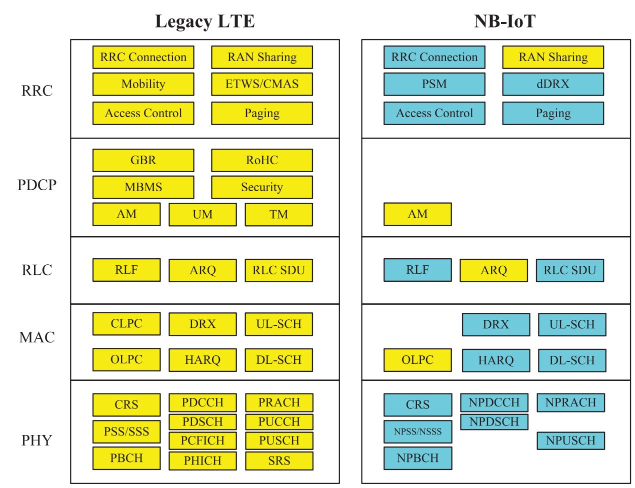

Fig. 6. Protocol layer comparison between legacy LTE and NB-IoT. The blocks with different color from LTE in NB-IoT mean that they are either newly introduced features or changed.

bytes once a day, the life of the battery with 5 Wh capacity is estimated to reach 12.8 years. It is worth clarifying that this prediction is only based on the simulation for one extreme case in which the device basically does not work. In real applications, the battery life prediction is rather complicated since there are many factors that need to consider.

C. Low Cost

As a latecomer of the IoT market, NB-IoT has to control its cost for dealing with the pressures of the other newcomers, such as ZigBee, Thread, BLE, etc., whose all-in-one price is around \$2 U.S., and individual price is no less than \$1 U.S. The chip cost has a close relationship with the area of the integrated circuit (IC). Cutting cost down is not easy for NB-IoT since it roots in the complicated LTE specification. This objective is eventually achieved based on decreasing system performance and simplifying protocol volume.

Decreasing system performance mainly consists of three aspects of contents. First, NB-IoT only keeps one transceiver that is shared by both the uplink and the downlink, while the legacy LTE design has to consist of two ones which respectively correspond to the different links. This is because NB-IoT changes to only support half-duplex frequency division duplex transmission mode, which means that the uplink and the downlink operate in different frequency band, but cannot work at the same time. In contrast, the original LTE standards need to support either full-duplex frequency division duplex or full-duplex time division duplex. Reserving only one transceiver also lowers the power consumption of the RF unit, which makes it possible to use low-price low-end power amplifier (PA). The downside is incapable of simultaneously receiving public information and user information. Second, NB-IoT only supports low data rate application, which is decided by the lower sampling rate and the smaller transfer block size. Lower data rate substantially drops off the demands for high-capacity on-chip flash and memory, which in general occupy the majority of the chip areas. Third, NB-IoT gets rid of the IP multimedia subsystem functionality, which further reduces the chip area but also loses the support to the voice service. Besides, despite the regulation of supporting maximum two antennas for NB-IoT in Release 13, currently the mainstream NB-IoT chip vendors tend to keep only one antenna, which also simplifies the implementation of the sophisticated antenna algorithm. Fig. 5 depicts the chip area reduction of UE Cat-NB1 compared to UE Cat-4.

The primary purpose of simplifying protocol volume is to decrease the UE computational capability, thereby relieving the requirement for the IC transistor counts. Fig. 6 compares the contents of all layers between the legacy LTE and the NB-IoT, and the detailed illustrations are given as below.

In physical (PHY) layer, NB-IoT only keeps five channels and three signals, whose explanations are listed in Table IV. Note that the uplink control channel is removed in NB-IoT. As a result, the uplink acknowledgment will be transmitted on NB-PUSCH, while scheduling request will have to be indicated based on random access procedure. Meanwhile, unlike LTE, the NB-IoT physical channels and signals are multiplexed in time. These changes significantly decrease the

TABLE IV
PHYSICAL CHANNELS AND SIGNALS OF NB-IOT

Channel		Usage
DL	Narrowband Physical Downlink Control Channel (NPDCCH)	Uplink and downlink scheduling information
	Narrowband Physical Downlink Shared Channel (NPDSCH)	Downlink dedicated and common data
	Narrowband Physical Broadcast Channel (NPBCH)	Master information for system access
	Narrowband Synchronization Signal (NPSS/NSSS)	Time and frequency synchronization
UL	Narrowband Physical Uplink Shared Channel (NPUSCH)	Uplink dedicated data
	Narrowband Physical Random Access Channel (NPRACH)	Random access

channel overheads. In addition, the PHY layer also simplifies the types of download control information (DCI) to only support three formats: N0, N1, and N2, which are respectively for the resource allocation of UL Grant, DL Grant, and Paging. The DCI in LTE system is blindly decoded at the UE side, so the DCI simplification reduces the computations. NB-IoT only uses low-order modulation modes: quadrature phase shift keying (QPSK) and binary phase shift keying, as well as simple coding scheme: tail-biting convolutional code for the downlink and turbo code for the uplink. These features also help to cut down the circuit complexity.

In media access control (MAC) layer, NB-IoT aims at reducing the overhead on the protocol stack processing flow. It only supports single process HARQ. Comparatively, the legacy LTE supports up to eight processes for HARQ. Single HARQ indicates that the UE has to wait until receiving NACK or ACK messages, which totally violates the LTE motivations of using multiple processes to improve the data rates. But the advantage is the complexity degradation. Besides, NB-IoT does not support the channel quality indictor (CQI) reporting and noncontention-based random access in MAC layer. Moreover, NB-IoT only supports open loop power control in uplink [51]. It means that UE does not need the eNB to send power control command but can determine the uplink transmission power according to the allocated modulation and coding scheme (MCS) and resource unit (RU), which is defined as the smallest amount of time frequency resource assigned to the UE. This scheme diminishes a lot of trouble compared to the close loop power control algorithm in the legacy LTE.

The simplifications of radio link control (RLC) layer, packet data convergence protocol (PDCP) layer, and radio resource control (RRC) layer have comparatively less effects on the chip cost. In RLC layer, NB-IoT only supports acknowledge mode (AM). It means that the system information, which works at transparent mode in the legacy LTE, now has to pass AM. It is natural to cut off unacknowledged mode for NB-IoT because it does not support the voice service in Release 13. In PDCP layer, NB-IoT makes substantial slashes. The original security and robust header compression functionalities are completely removed. In RRC layer, the most significant change is lacking of the mobility management. It means that NB-IoT does not support handover for the moment.

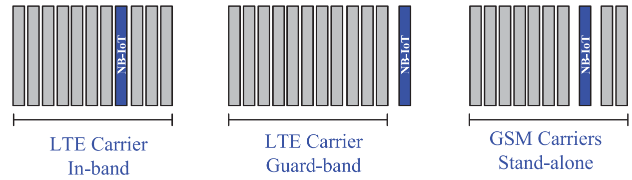

Fig. 7. NB-IoT deployment modes.

Apart from the cost of the chipset itself, there is an extra factor that is also worth taking into consideration. That is the network installation and maintenance cost. Compared with LoRa, NB-IoT has no necessity to construct the network from scratch. It can be deployed in three different operation modes [52]: 1) stand-alone as a dedicated carrier; 2) in-band within the occupied bandwidth of a wideband LTE carrier; and 3) within the guard-band of an existing LTE carrier, as shown in Fig. 7. In stand-alone deployment, NB-IoT can be used as a replacement of one or more GSM carriers since the 2G network will be phased out in the near future. In in-band operation mode, one or more LTE PRBs can be reserved for NB-IoT. They share the total eNB power. In guard-band operation, NB-IoT will be deployed within the guard-band of an LTE carrier. It only requires that the LTE bandwidth is beyond 5 MHz.

D. Massive Connection

The supported connection number, 52 547 per cell site sector, is calculated based on the assumption of TR 36.888 for London, where the area of cell site sector is 0.866 Km^2, the household density per Square Km is 1517, and the number of devices in a household is 40. This objective is achieved based on the following three key factors.

First, the data transmission characteristic of the MTC application plays an essential role for the massive connection. Such a communication model contains a large amount of users, but each user only transmits a small amount of data at low frequency, and they are insensitive to the transmission delay. Therefore, although the 50K users can camp on the same cell simultaneously, majority of them are in the sleep state. Since the eNB keeps their context information, the dormant users can immediately wake up and start to work once there are some data to upload.

Second, NB-IoT system exploits subcarrier-level uplink transmission scheme to sustain the large capacity, which is one key difference from the legacy LTE since the downlink transmission scheme is similar to LTE except for some restrictions. The resource scheduling unit in the NB-IoT uplink is subcarrier (or tone) instead of PRB, so as to provide better granularity and higher utilization. By this way, although the NB-IoT only has 180 kHz bandwidth, it can still simultaneously serve multiple UEs. NB-IoT supports two schemes: 1) optional multitone transmission and 2) mandatory single-tone transmission. Both schemes are based on SC-FDMA. For the multitone transmission, one UE can be allocated multiple tones with 15 kHz subcarrier spacing, 0.5 ms time slot and 1 ms subframe as LTE. For the single-tone transmission,

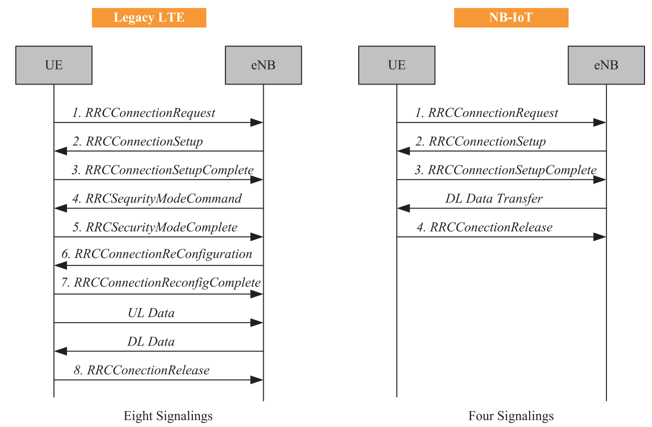

Fig. 8. Signaling comparison of legacy LTE and NB-IoT in downlink CP.

NB-IoT supports two numerologies: 15 and 3.75 kHz, and one UE can only use one subcarrier. The 15 kHz numerology is identical to LTE while the 3.75 kHz numerology uses 2 ms slot duration. If the 3.75 kHz single-tone scheme is exploited, one eNB can support the parallel transmissions of up to 48 UEs.

Third, NB-IoT simplifies signaling overhead, which can also improve the spectrum efficiency. Fig. 8 takes the control plane (CP) as one example and presents the signaling interaction of LTE and NB-IoT. It can be clearly seen that the LTE uses eight signaling messages while the NB-IoT only uses four signaling messages. Less signaling number is helpful to release the resources as earlier as possible so that the eNB can accommodate more UEs.

IV. Open Issues

Although the aforementioned key technologies pave a prospective way for NB-IoT toward the expansive MTC markets, they only qualitatively prove the feasibilities of the objectives. As a newly developing technology, there are still a lot of issues that need to investigate. For example, how much performance can be acquired on Earth? what optimizations can be performed to obtain more benefits? what effects can be derived when combining with other technologies? which challenges are left in the implementations and applications? In this section, we will survey all of these problems and give potential solutions.

A. Performance Analysis

Performance analysis is critical for the broad use of NB-IoT. It can help to detect performance bottleneck and execute application-aware performance tuning ahead of real deployment [53]. Currently, the majority of the related works are based on modeling, while the minority are tested in field by using software design radio (SDR) platform.

Modeling-based methodology usually starts from setting up simulation parameters, and then studies the performance of different channels under given link budgets. Different channels have different measurements because they correspond to different functions. The emphasis is to generate precise

TABLE V
Common Simulation Parameters

Parameter	Value
Carrier Frequency f_c	900 MHz
NB-IoT Bandwidth	180 kHz
Channel Model	Typical Urban (TU)
Doppler Spread	1 Hz
DL Antenna Configuration	1 Tx, 1 Rx (Stand-alone) 2 Tx, 1 Rx (In-band/Guard-band)
UL Antenna Configuration	1 Tx, 2 Rx
Transmit Power	43 dBm (DL, Stand-alone) 46 dBm (DL, In-band/Guard-band) 23 dBm (UL)
Noise Figure	5 dB (DL) 3 dB (UL)

TABLE VI
Performance for Downlink in NB-IoT

		Stand-alone		In-band	
MCL		144 dB	164 dB	144 dB	164 dB
Target SNR		15.4 dB	-4.6 dB	7.4 dB	-12.6 dB
NPSS NSSS	Detection Prob.	100%	99.8%	100%	99.5%
	Time (90% users)	84 ms	264 ms	84 ms	1284 ms
NPBCH	BLER	0.74%	1%	0.6%	0.4%
	Detection Period	10 ms	320 ms	20 ms	1920 ms
NPDCCH	BLER	1%	0.5%	0.52%	0.6%
	Transmission Duration	1 ms	128 ms	4 ms	256 ms
NPDSCH	Coding Rate	0.58	0.39	0.34	0.42
	Modulation	QPSK	QPSK	QPSK	QPSK
	RB	4 ms	6 ms	10 ms	8 ms
	Repetitions	1	32	1	128
	BLER	8.07%	9.58%	9.54%	7.43%
	TTI	4 ms	254 ms	12 ms	1364 ms
	Data Rate	156.28 kbps	2.42 kbps	51.26 kbps	461.5 bps

modeling for each channel according to the protocol characteristics. Before digging into the complicated channel modeling problem, we first give a brief description about the simulation parameters. In general, they are composed of carrier frequency, system bandwidth, transmit power for eNB and UE, propagation model, Doppler spread, antenna configuration, and noise figure for uplink and downlink. The Doppler spread is used to denote the speed of the UE relative to the base station, and lower value means lower mobility. Different operation modes correspond to different transmit power of eNB. The value of 46 dBm is a typical setting for eNB, but for in-band and guard-band operations, it is shared by LTE and NB-IoT. Taking a 10 MHz LTE channel as example, each PRB can only be allotted with 29 dBm. This may be too low to achieve good results, thus, a power boosting of 6 dB is regularly adopted for the NB-IoT PRB to improve performance. The noise figure is of key importance since it greatly impacts the performance by deciding the data rate, repetition number, etc. Table V lists the common assumptions regarding the simulation parameters.

The subsequent channel modeling is often built on the basis of each channel functionality. The performance metrics are either duration time for control channels at given block error rate (BLER) and target signal to noise ratio (SNR), or data rate for shared channels at different configurations.

TABLE VII
PERFORMANCE FOR UPLINK IN NB-IOT

		15 kHz		3.75 kHz	
NPUSCH	MCL	144 dB	164 dB	144 dB	164 dB
	# Tones	3	1	1	1
	Target SNR	3.5 dB	-11.8 dB	14.3 dB	-5.7 dB
	Coding Rate	0.43	0.52	0.87	0.52
	Modulation	QPSK	QPSK	QPSK	QPSK
	RB	32	80	48	80
	Repetitions	1	64	1	16
	BLER	9%	1.5%	1%	0.7%
	TTI	32 ms	5120 ms	192 ms	5120 ms
	Data Rate	28.43 kbps	192.4 bps	5.2 kbps	193.9 bps

Tables VI and VII illustrate one group of channel performance evaluation results for both downlink and uplink under some specific SNR and BLER [29]. Regretfully, it only simply gives out the final results without the analysis procedure. This is also the common drawback of some other similar works [50], [52], [54], [55], causing their results to differ a lot at great extents. Therefore, building analytical model or deducing closed-form formula based on given parameters can be referred to as one key research direction for this area. Furthermore, most of these works are done by only taking one single device as the research object, but lacking of the system perspective. It would be more significant to study the overall performance assuming around 50K devices to be distributed within one cell in the manner of stochastic geometry. This is also an unresolved research issue.

In addition to the modeling-based campaign, some other works aim at developing the toolkit and simulator for NB-IoT. Miao *et al.* [50] exploited OPNET simulation platform to build an NB-IoT system model, which consists of UE, eNB, core network, cloud platform, and vertical industry center. Basic on this platform, it is verified that the NB-IoT network indeed outperforms the LTE network with different channel width in terms of coverage range, channel utilization, and queuing delay. Krasowski and Troha [56] developed a downlink simulator for NB-IoT network using MATLAB. They make detailed implementations for both eNB-side and UE-side functions, including all physical channels and signals, resource scheduling, and equalization. With this simulator, they evaluate the relationship of BLER, SNR, and repetition times on different channels. Although these outstanding works provide good start points to explore the NB-IoT performance, their simulators are not universal enough to be extensively used. In contrast, the well-known network simulator ns-3 is more popular [57], however, there is no available NB-IoT module that can be integrated into it by far. It can be viewed as another potential research direction.

There are still some works devoting to make field tests based on SDR platform. Aalto University declares that they have implemented a prototype [58] for NB-IoT system using normal desktop computer and universal software radio peripheral [59], which are connected over Ethernet. The experiments made on the testbed show that the NB-IoT coverage improvement is limited by the channel estimation quality and coherence time of the channel [6]. Lauridsen *et al.* [60] focused on what kind of coverage and capacity can be achieved in a realistic scenario. They employ the commercially deployed LTE sites' configuration and location in a rural area, and calibrate the simulation using drive test measurements. Their tests reveal that NB-IoT can provide better coverage performance than LTE-M, but the costs are the lower number of supported devices per sector and higher device power consumption as compared to LTE-M. In spite of these findings, they claim that the NB-IoT still can support 25K devices and device battery life of above five years. In future, we expect more performance reports based on real deployments.

B. Design Optimization

Although NB-IoT is designed to reuse the LTE functionalities extensively, it still introduces many new features and makes some key differences to satisfy the objectives of super coverage, super capacity, low power, and low cost. These newly introduced characteristics ask for problem rediscoveries and novel contributions for design and optimization.

1) System Acquisition: The procedure of system acquisition for UE, including cell search and initial synchronization, mainly happens at either power-up or wake-up in response to data transfer request or paging timer expiration. It is the first step of baseband operations, so plays essential roles in the NB-IoT working flow. Since the NB-IoT changes the system bandwidth and introduces two new synchronization signals NPSS and NSSS, the original design for LTE is not suitable any more. Furthermore, the NB-IoT still faces three primary challenges. The first one is that the NB-IoT devices tend to use cheap crystal oscillators for reducing cost. They are generally incapable of realizing temperature compensation, causing large frequency offset. The second one is that the NB-IoT devices tend to work at low SNR scenarios for extending coverage, resulting in the accuracy impairments. The third one is that the NB-IoT devices tend to complete the initial acquisition at lowest possible latency, because the RF-transceiver, which dominates downlink power consumption of the UE, has to be turned on throughout this time.

Although there are several classical solutions for timing synchronization, including matched-filter (MF), differentiation, and maximum-likelihood (ML) detection, some optimizations have been done for resolving the aforementioned challenges. Ali and Hamouda [61] proposed to use averaging MF to tackle the tradeoff between performance and processing time. The final decision statistic is obtained by averaging the MF outputs over consecutive windows, while the window selection is fulfilled by using the divide-and-conquer method to find out the correct pattern of the possible frame timing and meanwhile reduce the computational complexity. Kroll *et al.* [62] found out that the auto-correlation detectors show low complexity from a signal processing point of view at the price of a higher signal latency, so they propose an ML-based cross-correlation detectors to achieve low latency but sacrifice some complexity. They present the hardware implementation by using VHDL and claim that the average latency of their proposal is roughly a factor of two below the value of auto-correlation scheme. Yang *et al.* [22] proposed a hybrid solution to enhance the system acquisition for NB-IoT. They find out that the acquisition performance is influenced by two factors: 1) the geometry factor and 2) the frequency offset factor. Based on the two factors, they derive different operating regions in which the performance of different techniques, MF and differentiation, can be maximized. So in their proposal, both techniques are employed. This also increases the hardware complexity.

Overall, to improve accuracy and reduce latency, the complexity has to be increased. Further comparison should be made between the increased power consumption induced by extra circuit logic and the reduced power consumption on the RF-transceiver due to reduced operating time.

2) Random Access: In contrast with the system acquisition that is the initial operation from the downlink point of view, random access is the first step for the uplink transmission. In NB-IoT, a new single tone uplink transmission scheme with frequency hopping is introduced to avoid the PA backoff by reducing the peak-to-average power ratio. Therefore, new random access preamble design and new detection algorithm are needed. Although the basic ideal is still based on the Zadoff–Chu sequences, there are two tradeoffs that need to investigate. The first one is the frequency hopping steps, which impacts the time-of-arrival (ToA) estimation range and accuracy; and the second one is the detection threshold, which impacts the misdetection and false alarm rate.

Lin *et al.* [63] presented their design for NB-IoT random access mechanism. The simulation result reveals that the detection probabilities exceed 99% while the false alarm probabilities are well below 0.1% according to their proposal. They also claim that the ToA errors are within ± 3 μs. Kim *et al.* [64] investigated the preamble collision problem and propose an enhanced access reservation protocol (ARP) with a partial transmission mechanism. The results show that their proposal outperforms the conventional ARP, in particular in heavier system loads.

3) Link Adaptation: Link adaptation is an important concept in communication system by adjusting the transmission schemes to adapt for the channel conditions [79]. In legacy LTE system, the UEs report CQI periodically or aperiodically. Based on the CQI report, eNB select a proper MCS level for the downlink transmission to make sure UEs can decode it with a BLER not exceeding 10%. The MCS table is given in the specification. By reading the MCS index, the UEs can derive the MCS configuration.

However, one of key technologies in NB-IoT is introducing retransmission to extend coverage. Consequently, the link adaptation for data transmission can be carried out in two dimensions: 1) MCS selection and 2) repetition number selection, which is different from the current LTE system, causing the existing link adaptation mechanism to be inappropriate. The straightforward solution is to fix one item first, and then change another one. But this kind of handling incurs additional signaling, which will consume more power and degrade the spectral efficiency, so it is necessary to design a new scheme to optimize the link adaptation.

Mu *et al.* [65] investigated the problem for the first time. They provide a static method for the eMTC downlink. Yu *et al.* [51] proposed a dynamic scheme for the NB-IoT uplink. Their proposal consists of inner loop link adaptation and outer loop adaptation. The former is to cope with the fast BLER variation by periodically adjusting the repetition number, and the latter coordinates the MCS level selection and the repetition number determination. However, according to Release 13, both MCS and repetition number are specified by the eNB through NPDCCH before the NPDSCH transmission. In other words, the current NB-IoT specification does not yet support this kind of dynamic adjustment.

C. Combination With Other Technologies

The first specification of NB-IoT is designed for low-end MTC applications, but as time goes on, the NB-IoT is possibly expected to sustain richer scenarios with better performance, such as larger capacity and smaller latency compared to the current version. These limitless objectives are difficult to accomplish purely depending on the NB-IoT itself. Thus, it can take the combination with other advanced technologies into consideration.

1) Nonorthogonal Multiple Access: In the NB-IoT uplink, the system bandwidth can be equally divided into 48 or 12 subcarriers relying on the configuration of 3.75 or 15 kHz subcarrier spacing. Each subcarrier can only be occupied by one single UE. It may not be able to cope with the expected increase in the number of MTC devices. Moreover, the limited number of subcarriers also leads to the increase of medium access delay. To tackle this issue, a promising approach is to use power-domain nonorthogonal multiple access (NOMA) [66] in NB-IoT networks so that multiple UEs can share the same subcarrier.

NOMA is an emerging technology to be designed for accommodating more devices in the 5G era. The receiver can receive messages from multiple transmitters on the same subcarrier and at the same time. This is only allowed when the receiving power from different transmitters are different in the eye of the receiver, which can use successive interference cancellation (SIC) to decode them sequentially. The main idea is to decode the higher receiving power message first, and regard the other messages as the noise. After decoding the higher receiving power message, the receiver subtracts it from the receiving power, and then starts to decode the next higher receiving power message. Comparing to orthogonal multiple access techniques, such as OFDMA and SC-FDMA, NOMA can provide larger connectivity.

Mostafa *et al.* [67] proposed the first study for the combination of NOMA and NB-IoT to improve capacity. Two kinds of devices, massive MTC (mMTC) and ultrareliable and low latency communications (URLLCs), are assumed to coexist in the same cell. One mMTC can share the subcarriers with one URLLC, and the URLLC has larger transmit power. The research target is to maximize the connections, meanwhile satisfying the quality of service and transmission power constraints. The authors decompose the problem into two subproblems and propose algorithms to solve

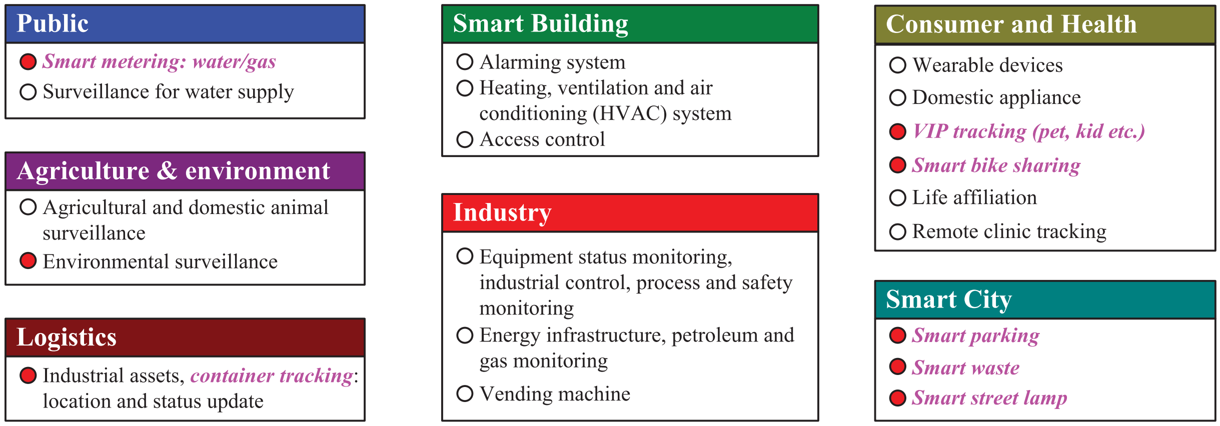

Fig. 9. Seven categories and 24 applications for LPWA scenarios identified by GSMA. The solid circle means that there are already NB-IoT solutions for the corresponding fields.

them. The simulation results show that the capacity can be improved by two factors.

SIC is the key technique enabling the power-domain NOMA, but it is not new and not limited to NOMA. Hu *et al.* [68] also exploited SIC to carry out the study of positioning for NB-IoT, which is viewed as the new feature in the future Release 14.

2) Device-to-Device Communication: In addition to NOMA, another form of technology which has gained high momentum in the evolution toward 5G era is device-to-device (D2D) communication, where devices can communicate directly over cellular resources, Wi-Fi, or BLE technologies, without routing the data over the BS. The D2D technology can fulfill proximity communications, so it can bring out the following profits: higher data rate, more reliability and energy savings, reduced connections, and possibility for instantaneous communication between devices. Therefore, combining with D2D can benefit the NB-IoT system in terms of latency, power, and reliability.

Militano *et al.* [69] discussed the security issues of this combination. They divide the NB-IoT UEs into different levels, where some of them are only allowed to communicate with other peers using LTE PRBs, and some of them are allowed to talk with eNB using normal NB-IoT subcarriers. The authors focus on the risk of threats to privacy and security. They introduce reliability and reputation notions to model the level of trust among UEs in an opportunistic hop-by-hop D2D-based content uploading scheme. Social awareness of devices is regarded as a means to enhance the identification of trustworthy nodes. The evaluation reveals that their proposal can drastically reduce the negative effects due to malicious nodes.

Petrov *et al.* [70] studied the gains of this combination. The main point is to let the vehicles act as relay nodes of the NB-IoT UEs. The authors offer mathematical analysis to prove the benefits at several important metrics of interest, such as energy efficiency, transmission latency, and connection reliability.

D. Implementation and Application

According to GSMA [71], totally seven categories and 24 cases are identified for the potential LPWA solutions, as depicted in Fig. 9. Among them, we find out that NB-IoT has been deployed in some key applications, such as smart parking [72], smart waste [73], smart street lamp [74], environmental monitoring [75], VIP tracking [76], smart bike sharing [33], container tracking [77], and smart metering [34], but it is still far from the large-scale deployments. Although it can be attributed to many reasons, our insights are twofold: one is due to the comparatively higher chipset prices, and another is due to some intrinsic limitations in the standard.

At present, many semiconductor vendors have shipped NB-IoT chipsets or modules into the market, but their prices go far beyond the expectations. This phenomenon is partly caused by the low integration during the implementation. Hence, a low-power fully integrated transceiver would notably cut down the cost. However, three challenges make it hard to design. First, owing to signal attenuation induced by the long communication distance, the receiver should achieve high sensitivity under rigorous power limit, but it is difficult to guarantee both high sensitivity and low power. Second, low out-of-band emission is required for the transmitter to be compatible with the guard-band or in-band deployment modes, but it is difficult to achieve under the conventional transmitter architecture. Third, to reduce power consumption, the NB-IoT phased-locked loop frequency synthesizers should use the Class-C voltage controlled oscillator (VCO), but it is difficult for the VCO to successfully start up and settle in the Class-C mode. In addition to it, even if with the available chipsets and modules, lacking of a scalable and easy-to-use development board as well as development platform would also hinder developers and researchers from conveniently executing the trials.

Some advancements have been made toward both of the issues. Recently, Song *et al.* [78] presented a fully integrated 750–960 MHz transceiver for single-tone NB-IoT applications, and Chen *et al.* [48] released a prototype, including NB-IoT developing board, cloud platform [80], application server, and user app. These works will help to accelerate the NB-IoT deployments in the near future.

In addition, we still spot some intrinsic limitations about the NB-IoT standard, which will also impact its application scenarios. We briefly outline them as follows.

1) Security and Privacy: This is one of the top concern related to NB-IoT systems from the society. Besides eavesdropping, which also occurs in the other wireless technologies, the strictly constrained nature of the devices and the narrow bandwidth make it very challenging to offer effective security mechanism via simple algorithms in limited room for message exchanges.

2) Excessive Latency: Although the NB-IoT standard specifies the maximum latency of 10 s for exceptional reports, the actual transmission delay may far exceed the expectation when huge amount of UEs are associated with one BS. This is mainly induced by the contention-based random access mechanism and the limited time/frequency RUs, which tends to cause the uplink collision, preamble overlapping, and resource shortage, thereby leading to inestimable waiting time.

3) Downlink Inaccessibility: The low power advantage of NB-IoT is mainly derived from the usage of PSM and eDRX. Whatever modes are used, as long as the device enters the deep sleeping status, any downlink signal has no way to wake up the device. It will limit its application in emergency cases, such as eHealth. The potential resolutions demand for the novel wake-up circuit techniques.

V. Conclusion

LPWA networks are regarded as the effective way to cater for the expansive low-end MTC applications. Currently, several commercial providers exploit different innovative techniques in their LPWA connectivity solutions. However, the variety of these solutions have resulted in a fragmented market, highlighting a dire need for standards. NB-IoT, as the new proposal of the 3GPP, is arousing extensive attentions since it comes into being. In this paper, we provided a comprehensive survey about its evolutions and key technologies. Moreover, we pointed out important challenges that NB-IoT faces today and possible directions to overcome them. We encourage further development in NB-IoT technologies to push the envelop of connecting massive number of devices in future.

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