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INVITED PAPER

Narrow Band Internet of Things

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ABSTRACT In this paper, we review the background and state-of-the-art of the narrow-band Internet of Things (NB-IoT). We first introduce NB-IoT general background, development history, and standardization. Then, we present NB-IoT features through the review of current national and international studies on NB-IoT technology, where we focus on basic theories and key technologies, i.e., connection count analysis theory, delay analysis theory, coverage enhancement mechanism, ultra-low power consumption technology, and coupling relationship between signaling and data. Subsequently, we compare several performances of NB-IoT and other wireless and mobile communication technologies in aspects of latency, security, availability, data transmission rate, energy consumption, spectral efficiency, and coverage area. Moreover, we analyze five intelligent applications of NB-IoT, including smart cities, smart buildings, intelligent environment monitoring, intelligent user services, and smart metering. Finally, we summarize security requirements of NB-IoT, which need to be solved urgently. These discussions aim to provide a comprehensive overview of NB-IoT, which can help readers to understand clearly the scientific problems and future research directions of NB-IoT.

INDEX TERMS Intelligent application, Internet of Things, LPWAN, LTE, NB-IoT.

I. INTRODUCTION

Over the last 20 years, the IoT technologies have developed significantly and they have been incorporated in various fields. Namely, almost everything can be connected through IoT network. IoT has achieved significant improvement in big data processing [1], heterogeneity [2], and performance [3]. From the perspective of transmission rate, the communication services of IoT can be coarsely classified into two categories: high-data-rate services (such as video service) and low-data-rate services (such as meter reading service) [4]. According to statistics by ATECH in 2017, the low-data-rate services represent more than 67% of total IoT services, which indicates that the low-data-rate WAN technologies are really desirable.

Recently, due to the development of IoT, the IoT communication technologies have become mature and widespread. From the perspective of transmission distance, IoT communication technologies can be categorized into short-distance communication technologies and WAN communication technologies [5], [6]. The former are represented by Zigbee, Wi-Fi, Bluetooth, Z-wave and etc. Their typical application is smart home. The latter are desired in low-data-rate services like smart parking mentioned above, which is generally defined by industry as the Low-Power Wide-Area Network (LPWAN) technology.

Thereinto, the development of LPWAN communication technology is especially obvious. From the perspective of frequency spectrum licensing, LPWAN technologies can be classified into two categories, technologies that work in unauthorized spectrum and technologies that work in authorized spectrum [7], [8]. The first category is represented by Lora, Sigfox and etc., of which most are nonstandard and custom implemented. The second category is generally represented by some relatively mature 2G/3G cellular communication technologies (such as GSM, CDMA, WCDMA and etc.), LTE technology and evolved LTE technology, which support different categories of terminals [9]. The standards for these authorized-spectrum communication technologies are basically developed by international standards organizations such as 3GPP (GSM, WCDMA, LTE and evolved LTE technology, etc.) and 3GPP2 (CDMA, etc.) [10].

The Narrow-Band Internet of Things (NB-IoT) is a massive Low Power Wide Area (LPWA) technology proposed

TABLE 1. Brief history of development and course of standardization of NB-IoT.

Standard number	Start time	Freezing time	Version	Technologic fields of concern
22.868	2005	2008	R8	Billing, addressing, security, communication mode, massive user
33.812	2007	2009	R9	Remote subscription management, security requirements, security architecture enhancement
22.368	2009	2015	R10	General and exclusive service requirements
23.888	2009	2012	R10	Strucutre enhancement of network system, signaling congestion in core network and congestion control
37.868	2010	2012	R11	Service features and modeling, access network enhancement and congestion control
43.868	2010	2014	R12	Service features and modeling, GERAN enhancement (such as resource allocation, overload and congestion control, addressing format and energy-saving mode)
22.988	2011	2015	R12	Numbering and addressing
36.888	2011	2014	R12	Service features and modeling, assumption on coverage enhancement, design thought on low-cost MTC terminals (such as single-radio frequency link, half-duplex, lower band width, lower peak rate, lower transmitting power and less-jobs mode)
22.888	2012	2014	R12	Architecture of network system, localization and IMS enhancement
23.887	2012	2014	R12	Small data- terminal triggering enhancement (SDDTE), monitoring enhancement (MONTE), optimized design for power consumption at terminals (UEPCOP), group features enhancement (GROUP)
33.868	2012	2014	R12	Security requirements, security architecture enhancement
33.187	2013	2015	R12	Security requirements, security architecture enhancement
37.869	2013	2014	R12	Signaling editing, UEPCOP
33.889	2014	2015	R13	GROUP, MONTE, opening of service ability
23.769	2014	2015	R13	GROUP
23.789	2014	2015	R13	MONTE
23.770	2015	2015	R13	Discontinuous reception of expansion (eDRX)
43.869	2014	2015	R13	Typical use case and service model, GERAN UEPCOP enhancement
45.820	2014	2016	R13	Enhanced indoor coverage, supporting massive small-data terminal, lower terminal complexity and cost, higher power utilization ratio, latency feature, compatibility with existing systems, architecture of network system (prototype of NB-IoT)
22.861	2016		R14	Typical use case and service requirements for mMTC
22.862	2016		R14	Typical use case and service requirements for uRLLC

by 3GPP for data perception and acquisition intended for intelligent low-data-rate applications. The typical applications are smart metering and intelligent environment monitoring [11], [12]. The NB-IoT supports massive connections, ultra-low power consumption [13], wide area coverage and bidirectional triggering between signaling plane [14] and data plane [15], [16]. Besides, it is supported by an excellent cellular communication network [17]. Therefore, NB-IoT is a promising technology [18].

A. BRIEF REVIEW OF NB-IoT DEVELOPMENT HISTORY AND STANDARDIZATION

For a long time, the cellular mobile communications mainly supported human-oriented voice service and mobile broadband service. Since 2005, 3GPP started a deep research on cellular network (such as GSM, UMTS and LTE) for Machine-Type Communication (MTC) services. The relevant feasibility and improvement research [19] aim to let MTC become an important component in 5G networks [20], as shown in Table 1 [21]. Based on the early deployment of MTC, the preliminary work of 3GPP (R8-R11) mainly focuses on problems such as overload and congestion on data and signaling planes, and numbering and addressing of resource shortage during synchronous access of numerous terminals to the network. After further refining and specifying of demands [22] and features of MTC service, in R12 3GPP announced the enhancements of GSM access network related to the design of low-cost MTC terminals,

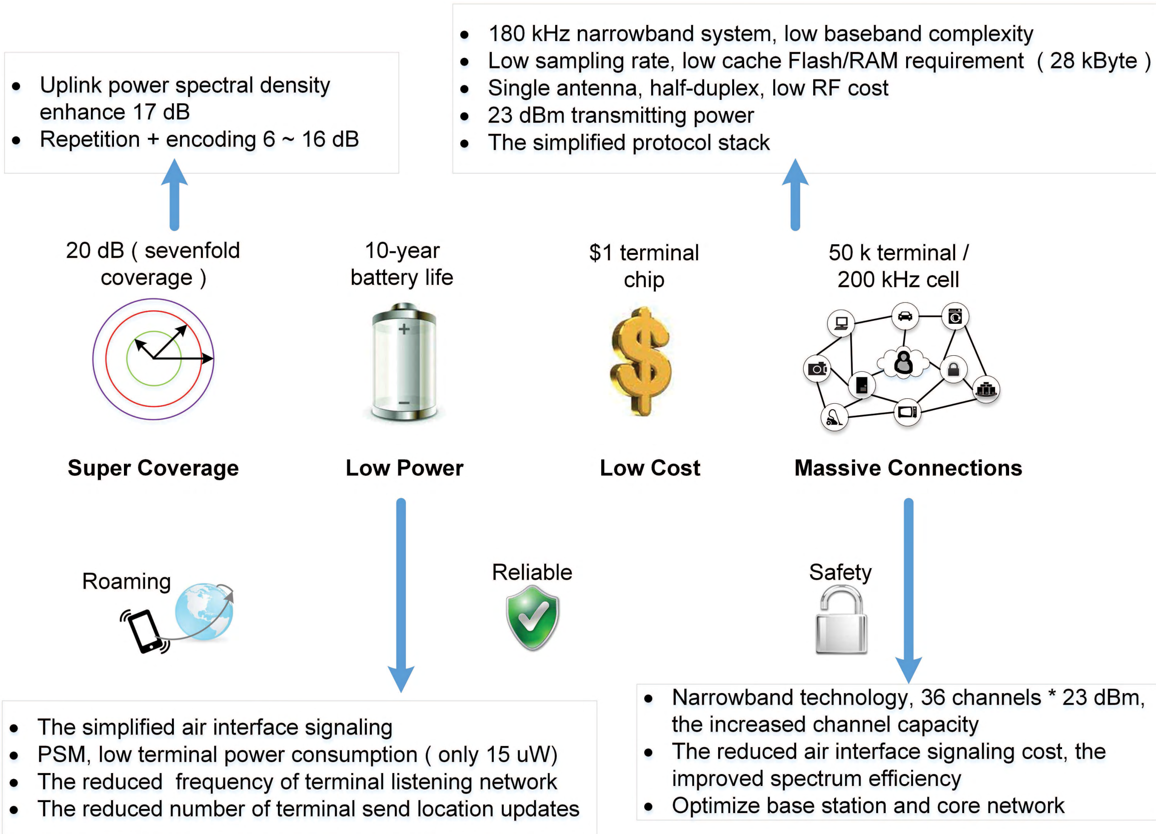

FIGURE 1. **Main features of NB-IoT.**

requirements for security and network system architecture. Promoted by non-3GPP LPWA technology (such as LoRa and Sigfox), in R13 3GPP set 5 objectives for MTC, including enhanced indoor coverage, supported massive small-data terminals, lower terminal complexity and cost, higher energy efficiency and supported various latency features. The R13 also defines 3 kinds of new narrow-band air interfaces, including GSM-compatible EC-GSM-IoT, LTE-compatible eMTC and brand new NB-IoT technology. Thereinto, NB-IoT is led by Huawei Technologies Co. Ltd, which is an outstanding private enterprise of China [23]. Compared to the non-3GPP LPWA technology, the 3GPP LPWA technology (represented by NB-IoT) draws more attention of industry, due to its software upgrading and core network reusing deployed in authorized frequency bands. It is predicted that cost degradation and commercial promotion of terminal chip for NB-IoT will be gradually realized in 2017. In February 2015, the IMT2020 work-group of China presented relevant concepts of NB-IoT. Since then, the IMT2020 has gradually perfected the research on technical proposal [24] and development in aspects of principle sample machine and terminal chip [25]. However, restricted by the time spot, R13 only provides a preliminary principle framework for a long-term perspective of NB-IoT. Therefore, many features still need to be improved in 3GPP R14. According to typical use and difference in service features [26], the MTC services defined by R14 can be further classified into two categories, mMTC and uRLLC. Besides, on the basis of five objectives of R13, R14 proposes functional requirements in aspects of localization support, multi-cast, mobility, higher data rate and link adaptation in order to make cellular IoT possess more suitable objects and application range [27]. In short, 3GPP adopts two-step strategy to cope with technological challenges brought by MTC services. The first step is a transition strategy that aims to utilize and optimize the existing network and technologies to provide MTC services [28]. The second step is a long-term strategy based on introduction of a new air interface technology for NB-IoT in order to support large-scale growth of MTC services and to maintain its core competitiveness toward non-3GPP LPWA technology [29].

B. NB-IoT FEATURES

Main NB-IoT features are shown in Fig. 1 and briefly introduced in the following.

1) LOW POWER CONSUMPTION

Using the power saving mode (PSM) and expanded discontinuous reception (eDRX), longer standby time can be realized in NB-IoT. Thereinto, PSM technology is newly added in Rel-12, where in the power saving mode the terminal is still registered online but cannot be reached by signaling in order to make the terminal deep sleep for a longer time to achieve the power saving. On the other hand, the eDRX is newly added in Rel-13, which further extends sleep cycle of terminal in idle mode and reduces unnecessary startup of receiving cell. Compared to PSM, eDRX promotes downlink accessibility significantly. The power saving mechanism of PSM and eDRX is as shown in Fig. 2 [30].

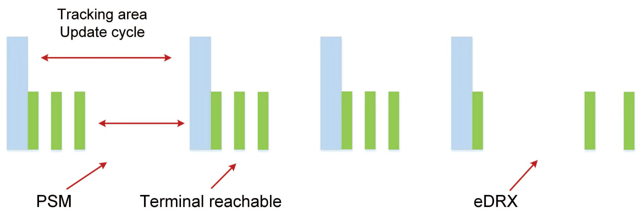

FIGURE 2. Power saving mechanisms of PSM and eDRX.

NB-IoT requires that the terminal service life of a constant-volume battery is 10 years for typical low-rate low-frequency service. According to simulated data of TR45.820, for coupling loss of 164 dB and using both PSM and eDRX, the service life of 5-Wh battery can be 12.8 years if a message of 200 byte is sent once per day by terminal, as shown in Table 2 [30].

TABLE 2. Estimation on service life of battery in integrated PA.

	Battery life / year		
Message size / message interval	Coupling loss = 144 dB	Coupling loss = 154 dB	Coupling loss = 164 dB
50 bytes / 2 hours	22.4	11.0	2.5
200 bytes / 2 hours	18.2	5.9	1.5
50 bytes / 1 day	36.0	31.6	17.5
200 bytes / 1 day	34.9	26.2	12.8

2) ENHANCED COVERAGE AND LOW LATENCY SENSITIVITY

According to simulated data of TR45.820, it can be confirmed that the covering power of NB-IoT can reach 164 dB in independent deployment mode. The simulation test was conducted for both in-band deployment and guard band deployment. In order to realize coverage enhancement, mechanisms such as retransmission (200 times) and low frequency modulation are adopted by NB-IoT. At present, the NB-IoT support for 16QAM is still in discussion. For coupling loss of 164 dB, if a reliable data transmission is provided the latency increases due to retransmission of mass data. Simulations for TR45.820 show the latency for irregular reporting service scenario and different coupling losses (header compressing or not) with reliability of 99%, Table 3 [30]. Currently, the tolerable latency in 3GPP IoT is 10 s. In fact, lower latency of about 6 s for maximal coupling losses can be also supported. For more details, please refer to simulation results of NB-IoT for TR45.820.

3) TRANSMISSION MODE

As it is shown in Table 4 [31], the development of NB-IoT is based on LTE. The modification is mainly made on relevant technologies of LTE according to NB-IoT unique features. The RF bandwidth of NB-IoT physical layer is 200 kHz. In downlink, NB-IoT adopts QPSK modem and OFDMA technology with sub-carrier spacing of 15 KHz [32]. In uplink, BPSK or QPSK modem and SC-FDMA technology including single sub-carrier and multiple subcarrier are adopted. A single sub-carrier technology with sub-carrier spacing of 3.75 kHz and 15 kHz is applicable to IoT terminal with ultra-low rate and ultra-low power consumption.

For sub-carrier spacing of 15 kHz, 12 continuous sub-carriers are defined. Accordingly, 48 continuous sub-carriers are defined for sub-carrier spacing of 3.75 kHz. Multiple sub-carrier transmission supports sub-carrier spacing of 15 kHz and defines 12 continuous sub-carriers which are combined into 3, 6, or 12 continuous sub-carriers. The coverage ability for 3.75-kHz spacing is higher than for 15-kHz spacing because of higher power spectral density. The cell capacity for 15-kHz spacing is 92% of that for 3.75-kHz spacing, but the dispatching efficiency and dispatching complexity are superior. Since the Narrow Physical Random Access Channel (NPRACH) has to adopt single sub-carrier transmission with spacing of 3.75 kHz, most of equipment preferentially supports single sub-carrier transmission with spacing of 3.75 kHz for uplink. After introducing single sub-carrier transmission with spacing of 15 kHz and multiple sub-carrier transmission, choice is made adaptively according to channel quality at terminal. The minimal dispatching unit for the Narrow Physical Downlink Shared Channel (NPDSCH) transmission is the resource block (RB), and the minimal dispatching unit for the Narrow Physical Uplink Shared Channel (NPUSCH) transmission is the resource unit (RU). In the aspect of time domain, for single sub-carrier transmission, the resource unit is 32 ms for sub-carrier spacing of 3.75 kHz and 8 ms for sub-carrier spacing of 15 kHz, and for multiple sub-carrier transmission, the resource unit is 4 ms for spacing with 3 sub-carriers, 2 ms for spacing with 6 sub-carriers, and 1 ms for spacing with 12 sub-carriers.

The protocol of NB-IoT high layer (the layer above physical layer) is formulated through modification of some LTE features, such as multi-connection, low power consumption and few data. The core network of NB-IoT is connected through S1 interface.

4) SPECTRUM RESOURCE

The IoT is the core service that will attract larger user group on communication service market in the future, therefore the development of NB-IoT has a great support from four largest

TABLE 3. Latency under environment with different coupling loss in service scenario of irregular report, where reliability of 99% is guaranteed.

Processing time	Send report headless compression (100 bytes load)			Send report header compression (65 bytes load)		
	Coupling loss/dB			Coupling loss/dB		
	144	154	164	144	154	164
Tsync/ms	500	500	1125	500	500	1125
TPSI/ms	550	550	550	550	550	550
TPRACH/ms	142	142	142	142	142	142
T uplink allocation/ms	908	921	976	908	921	976
T uplink data/ms	152	549	2755	93	382	1964
T uplink ACK/ms	933	393	632	958	540	154
T downlink allocation/ms	908	921	976	908	921	976
T downlink data/ms	152	549	2755	93	382	1964
Total time/ms	4236	4525	9911	4152	4338	7851

TABLE 4. Main technical features of NB-IoT.

Layer	Technical feature		
Physical layer	Uplink		BPSK or QPSK modulation
		SC-FDMA	Single carrier, the subcarrier interval is 3.75 kHz and 15 kHz the transmission rate is 160 kbit/s - 200 kbit/s
			Multi carrier, the subcarrier interval is 15 kHz, the transmission rate is 160 kbit/s - 250 kbit/s
	Downlink		QPSK modulation
			OFDMA, the subcarrier interval is 15 kHz, the transmission rate is 160 kbit/s - 250 kbit/s
Upper layer	LTE based protocol		
Core network	S1 interface based		
BPSK: Binary phase shift keying	NB-IoT: Narrow-band internet of things		QPSK: Quadrature phase shift keying
LTE: Long-term evolution	OFDMA: Orthogonal frequency division multiple access		SC-FDMA: Single carrier frequency division multiple access

telecom operators in China, who own respective spectrum resource for NB-IoT, as shown in Table 5 in detail [31]. Thereinto, China Unicom has opened commercial network for NB-IoT.

5) WORKING MODE OF NB-IOT

According to stipulations in RP-151621 of NB-IoT, NB-IoT currently supports only FDD transmission mode with bandwidth of 180 kHz and 3 following types of deployment scenes, which are shown in Fig. 3 [31], [33]:

- Independent deployment (Stand-alone mode), which utilizes independent frequency band that does not overlap with the frequency band of LTE;
- Guard-band deployment (Guard-band mode), which utilizes edge frequency band of LTE;
- In-band deployment (In-band mode), which utilizes LTE frequency band for deployment, and it takes 1 PRB of LTE frequency band resource for deployment.

6) FRAME STRUCTURE

The downlink of NB-IoT eNodeB supports E-Utran wireless Frame Structure 1 (FS1), as shown in Fig. 4 [34]. The uplink also supports FS1 for sub-carrier spacing of 15 kHz. However, for 3.75 kHz sub-carrier spacing, it defines a new kind of frame structure, Fig. 5 [34].

TABLE 5. Spectrum division for NB-IoT by telecom operators.

Operator	Uplink frequency band/MHz	Downlink frequency band/MHz	Bandwidth/MHz
China Unicom	909-915	954-960	6
	1745-1765	1840-1860	20
China Telecom	825-840	870-885	15
China Mobile	890-900	934-944	10
	1725-1735	1820-1830	10
SARFT	700	700	Undistributed
NB-IoT: Narrow-band internet of things			

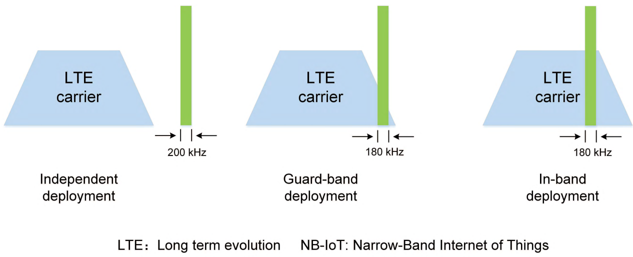

FIGURE 3. 3 Deployments supported by NB-IoT.

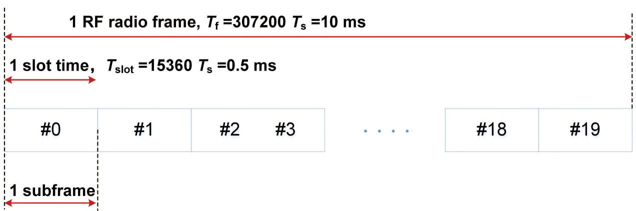

FIGURE 4. NB-IoT frame structure for sub-carrier spacing of 15 kHz for both uplink and downlink.

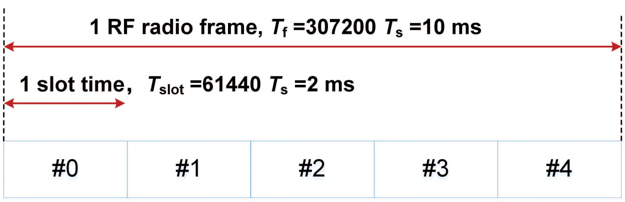

FIGURE 5. NB-IoT frame structure for sub-carrier spacing of 3.75 kHz for uplink.

7) NB-IoT NETWORK

The NB-IoT network is shown in Fig. 6 [31] wherein it can be seen that it consists of 5 parts:

- NB-IoT terminal. IoT devices in all industries have access to NB-IoT network as long as the corresponding SIM card is installed;
- NB-IoT base station. It mainly refers to the base station that has already been deployed by telecom operators, and it supports all three types of deployment modes mentioned before;
- NB-IoT core network. Through NB-IoT core network, NB-IoT base station can connect to NB-IoT cloud;
- NB-IoT cloud platform. NB-IoT cloud platform can process various services and results are forwarded to the vertical business center or NB-IoT terminal;
- Vertical business center. It can obtain NB-IoT service data in its own center and take control of NB-IoT terminal.

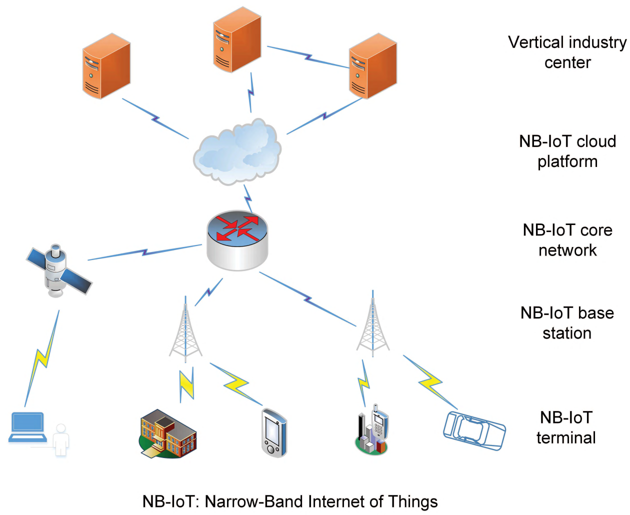

FIGURE 6. NB-IoT networking.

8) SEMI-STATIC LINK ADAPTATION

Most of the target service scenes of NB-IoT are mini-packet transmissions and it is hard for NB-IoT to provide long-term and continuous indication of channel quality change [35], so NB-IoT introduces coverage level instead of dynamic link adaptation scheme [36]. There are three kinds of coverage classes including normal coverage, robust coverage and extreme coverage which correspond to the minimum coupling losses (MCL) of 144 dB, 158 dB and 164 dB respectively, as shown in Fig. 7. Modulation, coding mode and repeat times of data transmission can be selected according to the coverage class of terminals and that is how the semi-static link adaptation is realized [36]. The NB-IoT base station configures one RSPP list which contains two RSPP threshold values to distinguish different coverage level.

9) DATA RETRANSMISSION

The NB-IoT adopts data retransmission mechanism to obtain time diversity gain and low-order modulation to improve demodulation performance and coverage performance [37], [38]. All channels support data retransmission. Besides, 3GPP also specifies the retransmission count and corresponding modulation mode for each channel, as shown in Table 6 [34].

TABLE 6. Times for retransmission supported by each channel.

Physical signal/physical channel name		Repetitions	Modulation
Downlink	NPBCH	Fixed 64 times	QPSK
	NPDCCH	[1,2,4,8,32,64,128,256,512,1024,2048]	QPSK
	NPDSCH	[1,2,4,8,32,64,128,192,256,384,512,768,1024,1536,2048]	QPSK
Uplink	NPRACH	[1,2,4,8,32,64,128]	–
	NPUSCH	[1,2,4,8,32,64,128]	ST:/4-QPSK and /2-BPSK MT:QPSK

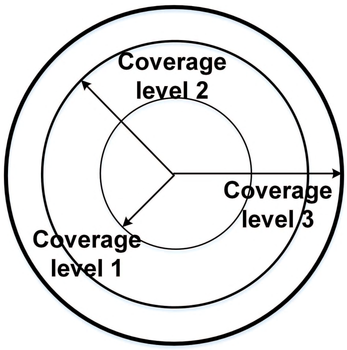

FIGURE 7. Coverage levels of NB-IoT.

C. BASIC THEORY AND KEY TECHNOLOGY OF NB-IoT

1) CONNECTION ANALYSIS THEORY

3GPP analyzed the number of connections that NB-IoT can reach when network supports terminal periodical report service and network command report service [39]. Assuming that services are evenly distributed within one day, NB-IoT can support 52547 connections per cell [11]. Actually, the assumption is more than ideal which almost ignores the burstiness of NB-IoT service. As a result, it is hard to generalize it at other application scenes. At present, there are few studies on the burstiness of NB-IoT service. However, research results of LTE-M and eMTC are still worthy of learning. In order to solve the overload of LTE access network when a large number of MTC terminals enter network simultaneously, researchers focused analyses on the load pressure of LTE RACH and its overload control mechanisms, such as classified controlled access, exclusive RACH resources, dynamic RACH resources allocation, exclusive backoff mechanism, time division access and active paging mechanism [19], [40]. Researches generally set service arrival process as a homogeneous/compound Poisson process or an independent Bernoulli process [41] with identical distribution [40] and retransmission user number and packet retransmission number at queue head or channel state (busy/idle) in a certain time slot as state variables to obtain a stabilized design scheme [42] on the premise of completing the multi-channel S-ALOHA steady-state performance analysis [43], [44]. The design scheme can be applied to the optimal design of LTE RACH [45]. However, when a large number of MTC terminals enter network simultaneously, then a large number of MTC terminals would simultaneously send transient and rapid session request to the network in a short time because of responding to the same incident or implementing relevant incident monitoring [46], [47]. This feature can be hardly described with classical homogeneous/compound Poisson process, which obstructs the direct application of network performance analysis method based on steady state assumption. Therefore a transient performance analysis method for multi-channel S-ALOHA for non-Poisson service is necessary [48], [49]. Due to the lack of actual application scenes, there are few studies on S-ALOHA transient performance analysis. In [50], for the first time, the authors gave the transient performance of a single-channel ALOHA under pulsed excitation through computer simulation, and defined the backlog fall time as an evaluation index of transient performance. In [51], the authors studied the transient performance of backlog user number of single-channel ALOHA for Bernouli process excitation through diffusion approximation. Based on 3GPP MTC reference service model (i.e., Beta distribution-like service model) [52], [53] gave the analysis methods for multi-channel S-ALOHA transient performance and LTE RACH throughput, latency and retransmission number through setting Mi(j) (i.e., the number of users that randomly access for the j-th time to the i-th RA slot) as a state variable. However, subsequent studies found that the bottleneck of uplink is not only RACH but also PDCCH with sparse resources when LTE carries MTC services. References [54] and [55] verified the load pressure of LTE/GSM RACH for constrained PDDCCH/AGCH by numerical simulation [56] and queue model respectively [57], [58]. In [59] and [60], the authors analyzed the four-step access process of LTE RACH for constrained PDCCH and gave the computing method for average throughput based on URN model. Restricted by complexity of analytic solution, RACH performance analysis for constrained PDCCH focuses more on steady-state solution under Poisson assumption and only [54] adapted Beta service model. Therefore, the research methods and conclusions mentioned above need to be further improved. In order to improve capacity analysis theory of NB-IoT, researchers study the maximal number of connections supported by NB-IoT RACH and the optimum resources allocation proportion for arbitrary random access strength excitation (including Beta-type service model), total constrained bandwidth and mutual restriction among NPRACH, NPDCCH, NPDSCH and NPUSCH.

2) LATENCY ANALYSIS THEORY

Besides number of connections, the 3GPP pointed out that theoretical computing model for uplink access latency is also necessary [40]. The uplink access latency is composed of system synchronization latency, broadcast information reading latency, random access latency, resources allocation latency, data transmission latency and feedback response latency [11]. A part of mentioned latencies denote deterministic processing latency, while another part denote latencies related to signal detection, and there are also random access latencies related to service behavior [43], [44]. The existing studies mainly focus on computing of mean value and variance of random access latency, while few studies focus on probability density function (PDF) of random access latency [38], [42]. In [42] and [37], the authors derived the probability generation function (PGF) of PDF of random access latency based on Markov process. In [61], in order to provide low-latency and high-reliability communication, an SDN-enabled network architecture assisted by MEC [62], which integrates different types of access technologies, is proposed. However, the computation complexity is too high. Moreover, it is almost insoluble when the number of users is too large. Assuming that both arrival time interval and back-off time follow negative exponential distribution, [41] derived the PDF of random access latency. In [43] and [63], the authors derived the probability distribution function of random access latency, assuming that the number of retransmission times is constant value or follows geometric distribution. The above-mentioned studies considered only uniform, exponential and geometric backoff mechanisms, but the restriction on maximal retransmission times was considered only in [45] and [38], which disagreed with actual protocol. In addition, the service models were always assumed as homogeneous Poisson processes or Bernoulli processes, so it is hard to extend them to the NB-IoT application scenes.Based on Beta-type service model, [52] gave the approximate form of CDF of random access latency after estimating maximal retransmission times of successful access to terminal through mean value latency. In [64], the authors derived the lower bound of random access latency through approximation of Beta distribution by piecewise linear function without considering the influence of maximal retransmission times. In short, the theoretical computing model of random access latency has not been completely solved yet even for the simplest Poisson service model and uniform backoff mechanism. Therefore, researchers focus more on the statistical properties of NB-IoT random access latency including mean value, variance, PDF and PGF for arbitrary random access strength excitation (constrained PDCCH and unconstrained PDCCH scenes are considered separately) to improve the latency analysis theory for NB-IoT.

3) COVERAGE ENHANCEMENT MECHANISM

The narrow-band modulation and sub-GHz deployment of NB-IoT can improve receiving sensitivity to enhance coverage ability. Besides, 3GPP proposed a new enhancement mechanism based on coverage classes (CCs), which is a new concept introduced for NB-IoT by 3GPP [11], [12]. Currently, there are few relevant researches on it, but actually, the essence of this mechanism is a kind of special link adaptation technology, i.e., terminals ascertain the coverage class according to transmission environment, and then implement corresponding coverage enhancement mechanism (such as blind retransmission and TTI bundling) [65], [66]. Unfortunately, 3GPP did not give the discrimination and upgrading mechanism and the performance evaluation is restricted to static analysis based on maximum coupling loss (MCL) [11], [67], [68]. As a result, dynamic working process of the mechanism cannot be effectively described. Therefore, researchers introduce research thoughts and methods in field of adaptive modulation and encoding into performance analysis and optimal design of enhancement mechanism based on coverage class [69], [70], aiming to develop a kind of coverage class discrimination/upgrading mechanism and coverage enhancement technology based on dynamic statistical multiplexing. There are three steps: 1) determination of optimum discrimination threshold of coverage class by referring to RSSI and SINR determined by building penetration loss (BPL); 2) dynamic adjustment of coverage class according to HARQ times in physical layer or ACK/NAK times in MAC layer; and 3) coverage enhancement according to current state and long-term statistical law of above indices, determining optimal transmission opportunity, retransmission times and transmission power, and completing performance analysis and determining the optimal value range of system parameters.

4) ULTRA-LOW POWER TECHNOLOGY

In order to achieve an ultra-low power consumption for NB-IoT, 3GPP introduced the power saving mode and expanded discontinuous reception on the basis of lower transmitting power [71]. However, simulation results indicated that the predicted service life of terminal equipped with 5-Wh battery can be 10 years if data is transmitted once per day, which is too ideal case for most of NB-IoT application [11]. Therefore, it is necessary to evaluate energy efficiency mechanism further and to propose improvement strategy, which is also one of the main tasks of 3GPP R14 [72]. Most of the existing works on DRX energy consumption model focus on power consumption level of a single terminal and the key point of modeling is the relationship between control signaling and terminal operating modes switchover [73], [74]. The energy consumption efficiency and trade-off between it and latency can be derived after getting stability probability and duration time of Markov chain for different states [75], [76]. Most of models mentioned above are based on Human Type Communications (HTC) service, such as mobile Internet services including VoIP, web browsing and video service, and they hardly consider the relationship between control signaling and NB-IoT application background (i.e., the correlation when a large number of NB-IoT terminals is responding to the same incident or implementing relevant incident monitoring). In other words, the energy consumption of a single NB-IoT terminal is not only influenced by its own operating mode switchover but also by operating mode switchover of relevant NB-IoT terminals. Therefore, researchers attempt to study space-time correlation of NB-IoT application scenes and its influence on operating modes of NB-IoT so as to analyze the group energy consumption level of NB-IoT terminals [77]. Using the group energy consumption, the individual energy consumption level of NB-IoT terminal can be analyzed. Finally, the design method for optimization of energy consumption of NB-IoT system and terminals can be completed based on that information. Besides, some studies indicate that NB-IoT terminal in idle state can complete an entire data transmission only after random access. In the case of strong service burstiness, the number of backoff times of terminal increases significantly during random access process [78], [79]. Since the power control strategy with power climbing mechanism is popular in random access processes the corresponding power consumption increases significantly, therefore, the evaluation of energy consumption level in random access process with power climbing mechanism is especially important for NB-IoT [80]. Consequently, most existing works determine the transmitting power of terminal according to link loss and capture effect, and then classify terminals based on transmitting power in order to complete power consumption analysis and optimization design for ALOHA with power ramp mechanism for multi-power terminal excitation through solving the steady-state equation under Poisson assumption. The transient process of ALOHA is seldom concerned [81], [82]. Therefore, on the basis of connection number analysis theory and latency analysis theory for NB-IoT, the energy consumption model and optimized design method for random access process of NB-IoT for arbitrary random access strength excitation still need to be studied in order to evaluate the energy efficiency level [83] and to improve the strategy of NB-IoT system comprehensively [84].

5) COUPLING RELATIONSHIP BETWEEN SIGNALING AND DATA

Except the above-mentioned problems, the Test Department of Chengdu Institute of Huawei Technologies Co., Ltd stated that a model that can describe the coupling relationship between signaling and data is desired to implement coupling simulation of signaling plane and data plane. The reason can be described as follows [85]. The signaling plane of most test equipment and simulation tools is separated from data plane, which only provides independent pressure tests for signaling plane and data plane but cannot realize the mutual triggering between signaling and data, especially for those signaling plane services triggered by user plane. As a result, when we want to test the influence of simultaneous access of massive MTC terminals to network, it is hard to simulate the actual load of present network and to reproduce overload of present network [86]. Most commercial software and instruments simulate specific protocol and scene based on user behaviors, but the relevance between signaling and data or service model is seldom concerned. In [87], the authors gave a green video transmission algorithm to improve spectrum utilization based on the analysis of video content. There are only a few studies on that subject, and most of them focus on brief accounting of signaling overhead, which still lacks modeling and analysis of relevance mentioned above [11], [88]. On the other hand, in order to reduce signaling overhead caused by simultaneous access of massive NB-IoT terminals, the signaling plane of NB-IoT needs to be edited and optimized. Hence, the relevance mentioned above is especially important. Therefore, researchers need to analyze the principal working process in physical layer and MAC layer of NB-IoT deeply to establish the dynamic signaling overhead model which can describe the relevance between signaling and data or service model [89], [90]. In the meantime, they also need to evaluate its performance in combination with sampling path theory and ergodic theory, so that a theoretical guidance for joint pressure test of signaling and data and congestion prevention is provided.

II. COMPARISON BETWEEN NB-IoT AND OTHER COMMUNICATION TECHNOLOGIES

A. COMPARISON BETWEEN NB-IoT AND eMTC TECHNOLOGY

1) DEVELOPMENT OF MTC TECHNOLOGY

Before the NB-IoT was proposed, the trend of Internet of everything in future IoT was highly recognized by industry. The machine-to-machine (M2M) communication was also considered as an important opportunity for standard ecological growth by 3GPP. In the era of Internet of everything, the LPWAN technology characterized by low cost, low power consumption, wide coverage and low rate plays an important role, therefore, 3GPP has been always promoting the development of MTC relevant technologies, and the efforts are mainly on two directions:

Direction 1: Research on further evolution of GSM technology and brand new access technology to face with the non-3GPP technological challenges. For a long time, the IoT services provided by 3GPP operators mainly relied on GPRS modules with a low cost. However, due to the appearance of new technologies such as Lora and Sigfox, the traditional advantages of GPRS modules in aspects of cost, power consumption and coverage ability are under threat. Therefore, 3GPP proposed a new SI (Study Item) - FS IoT LC on GERAN#62 conference held in March 2014. The new SI studies the feasibility of evolving GERAN system and new access system to realize enhancements such as lower complexity, lower cost, lower power consumption and stronger coverage.

Direction 2: Consideration of future alternative IoT module and studying of a low-cost and evolved LTE-MTC technology. After entering into development stage of LTE and evolved technology, 3GPP defined many terminal categories that apply to different service requirement scenes of IoT. The terminal Categories 1-5 with different rates are defined in Rel-8. In the evolved versions, terminal Categories 6 and 9 that support high bandwidth and high rate are added, and in the meantime terminal Category 0 that supports lower cost and lower power consumption (Rel-12) is also defined. On the basis of Category 0,a new SI - LTE_MTCe2_L1 - was proposed by 3GPP on GERAN#65 conference in September 2014 to study LTE-MTC technology with lower cost, lower power consumption and stronger ability further.

The NB-IoT is derived from the research on brand new access technology in Direction 1. Furthermore, except two directions above, 3GPP has always been studying the power saving technology with lower power consumption and synchronous upgrading of system architecture and network to support relevant evolved technologies.

2) ORIGIN AND DEVELOPMENT OF eMTC

The enhanced Machine Type Communication (eMTC) is an application scene of IoT which provides ultra-high reliability and low latency, and the emphasis of eMTC, is mainly on communication requirements.

The Internet of everything is an inexorable trend. The massive connections in the IoT will be widely applied in daily life via pet tracking, elderly caring and smart travel, or in vertical industry via industrial manufacturing and intelligent logistics. These applications require wider and deeper coverage ability. Namely, application scenes such as basement and outer suburbs should also be covered. These applications also require lower power consumption; for instance, in services like meter reading, the battery service life should be 10 years. Besides, larger scale of connections and lower cost are also required (LPWAN). The present cellular network technology cannot meet requirements of LPWAN in terms of coverage ability, power consumption, cost and etc.; therefore, the eMTC technology emerges.

The eMTC is an important branch of Internet of everything technology which is derived from LTE protocol. In order to accommodate the communications between things and further reduce the cost, the trimming and LTE protocol optimization are performed.The deployment of eMTC is based on cellular network, its user equipment can be directly connected into existing LTE network by supporting radio frequency of 1.4MHz and bandwidth baseband. The maximal peak rates for uplink and downlink supported by eMTC are 1 Mbps, which can support abundant and innovative IoT applications. The IoT applications such as Internet of Vehicles, smart health care and smart home produce massive connections, which exceed the communication requirements between human beings, and that is an important strategic direction for realization of the Big Connection objective of operators. The eMTC, as an emerging technology, widely supports physical connection of equipment with low power consumption in wide area cellular networks. In March 2016, 3GPP formally announced that the relevant contents of eMTC have been included in R13 and standards have been formally released. In the future, the relevant contents of eMTC will evolve the evolution of LTE protocol according to development in technologies, application scenes and etc.

The eMTC possesses four basic advantages of LPWAN: wide coverage, ability to support massive connections, lower power consumption and lower module cost. Due to the wide coverage, eMTC can obtain a transmission gain of 15 dB in comparison to the existing network under the same frequency band, which improves coverage ability of LTE network significantly. Moreover, one sector of eMTC supports nearly 100,000 connections. The standby time of modules of eMTC terminals can be up to 10 years. The large-scale connections bring rapid decrease in cost of module chips, and the target cost for one eMTC chip is about 1-2$.

The eMTC also possesses four differentiated abilities: high rate, mobility, locatability and voice supporting. As already mentioned, the maximal peak rates for uplink and downlink supported by eMTC are 1 Mbps, which far exceeds the rate of current mainstream IoT technologies such as GPRS and Zigbee. As a result, more abundant IoT applications can be supported such as low bit-rate video and voice. In addition, eMTC supports mobility in connected state. The seamless switch can be achieved to guarantee user experience. Since eMTC is locatable, localization can be achieved for TDD-based eMTC by using PRS measurement at base station side without adding new GPS chips. The low-cost localization technology benefits popularization of eMTC in scenes such as logistics tracking and freight tracking. The eMTC evolves from LTE protocol, so it supports VoLTE voice which can be widely applied to wearable devices in the future.

The eMTC can be deployed and upgraded directly on the existing LTE network and it can share site location and antenna feeder with existing LTE base stations. The advantages of low cost and rapid deployment help operators seize opportunities on IoT market rapidly expanding business boundaries, and also help third-party vertical industries to release more demands.

3) DIFFERENCE BETWEEN NB-IoT AND eMTC

a: COVERAGE

The design objective of NB-IoT is to achieve coverage enhancement of 20 dB compared to GSM. Hence, if the maximal coupling path loss of GSM is 144 dB, the maximal coupling path loss of NB-IoT should be 164 dB. Thereinto, the enhancement of downlink mainly relies on increase of the maximal retransmission times for each channel. Though the uplink transmitting power of NB-IoT terminals (23 dBm) is 10 dBm lower than that of GSM terminals (33 dBm), the transmitting bandwidth narrowing and increase of maximal retransmission times enable uplink to work under the maximal coupling path loss of 164 dB.

As for eMTC, the design objective is to achieve coverage enhancement of 15 dB compared to LTE whose maximal coupling path loss is 140 dB, thus the maximal coupling path loss of eMTC should be 155 dB. The coverage enhancement mainly relies on channel repetition, and the coverage is about 9 dB worse than coverage of NB-IoT.

In summary, the coverage radius of NB-IoT is about 4 times larger than that of GSM/LTE, while coverage radius of eMTC is about 3 times larger than that of GSM/LTE. The coverage radius of NB-IoT is 30% larger than that of eMTC. The coverage enhancement of NB-IoT and eMTC can be used to improve deep coverage ability of IoT terminals and coverage rate of network, or to reduce density of site locations and reduce network cost.

b: POWER CONSUMPTION

Due to the geographical location or cost, terminals are hardly updated which represents a challenge for most IoT applications. Therefore, the power consumption plays an important role in determining whether IoT terminals can be commercially used in special scenes.

As for NB-IoT, the design objective for service life of terminal battery in 3GPP standards is 10 years. The NB-IoT reduces power consumption using eDRX and PSM and improving the battery efficiency through improvement of PA efficiency by reducing the peak-to-average ratio, reducing periodic measurement times and supporting only a single process to achieve objective. However, in practice, the service life of battery is closely related to specific service model and coverage area of terminal.

Since, the ideal service life of battery for eMTC is also 10 years, it also introduces PSM and eDRX. However, the actual performance still needs to be evaluated and verified in different subsequent scenes.

c: MODULE COST

The NB-IoT adopts simpler modulation, demodulation and encoding method to reduce requirements on memorizer and processor. A series of methods are adopted, such as half-duplex mode, no-demand diplexer, reducing out-of-band indicator and congestion indicator. Under the present market scale, its module cost is lower than 5 $. In the future, the module cost might be further reduced with the expansion of market scale due to the scale effect. The specific amount and time will be determined by the speed development.

As for eMTC, the cost is also optimized according to IoT application requirements on the basis of LTE. Under market preliminary deployment scale, the module cost could be lower than 10 $.

d: CONNECTION COUNT

Connection count is the key factor for large-scale application of IoT.

As for NB-IoT, at the beginning, the preliminary objective was 50,000 connections per cell. Based on the preliminary computation and evaluation, the current version of NB-IoT can basically meet requirements. However, whether the design objective can be reached in practice depends on factors such as NB-IoT terminal service model in the cell. Thus further test and evaluation are still required.

The eMTC does not optimize the connection count exclusively for IoT. Currently, its predicted connection count is smaller than that of NB-IoT technology, and further test and evaluation are still required for specific performance.

e: FUNCTIONS TO BE ENHANCED

Localization: in R13 of NB-IoT technology, in order to reduce power consumption, PRS and SRS have not been designed. Therefore, NB-IoT can achieve localization only through E-CID at base station side with low accuracy. In the future, characteristics and design which can improve localization accuracy will be further considered.

Multi-cast: in IoT services, it is possible for base station to send the same data package to large amount of terminals simultaneously. The R13 of NB-IoT does not provide corresponding multi-cast service which might results in wasting of system resources and prolonging of the overall message transfer time. The R14 might consider multi-cast feature and improve relevant performance.

Mobility/business continuity enhancement: Actually, the R13 of NB-IoT is designed and optimized for static/low-rate users mainly without supporting neighborhood measurement reporting. Therefore, NB-IoT only supports reselection among cells in idle state but switchover among cells in connected state. In R14, the function of UE measurement reporting will be enhanced and switchover among cell in connected state will be supported.

f: VOICE SUPPORT

The voice rates of SD and HD VoIP are 12.2 kbps and 23.85 kbps, respectively, therefore, the whole network needs to provide at least 10.6 Kbps and 17.7 Kbps application layer rates to support SD and HD VoIP voice, respectively.

The uplink and downlink rates of NB-IoT at peak value are only 67 kbps and 30 kbps, thus, voice function cannot be supported under networking environment.

As for eMTC, the uplink and downlink rates of FDD mode are basically able to meet the requirements for voice, however, from the perspective of industry, the present support circumstances are quite limited. The TDD mode of eMTC, because of restricted number of uplink resources, has less capability to support voice than FDD mode.

g: MOBILITY MANAGEMENT

In NB-IoT R13, the cell handover and redirection cannot be conducted in connected state, and cell reselection can only be conducted in idle state. In subsequent versions, the industry might propose requirements for mobility management for connected state because of vertical industrial requirements.

Since eMTC technology is optimized and designed based on LTE, it supports cell handover in connected state.

TABLE 7. Comparison between NB-IoT and eMTC.

Technical index		NB-IoT	LTE FDD eMTC	LTE TDD eMTC(3:1)
Carrier bandwidth		200kHz	1.4MHz	1.4MHz
Peak rate	Uplink	66.7kbps	375kbps(half duplex)/1Mbps(full duplex)	200kbps
	Downlink	32.4kbps	FD:800kbps,HD:300kbps	750kbps
Coverage(compared with GSM)		Increased 20dB	Increased 11dB	
Power consumption		About 10 years	About 10 years	
Module cost		Less than $5 initially	Weaker than NB	
Connection		About 50 thousands/cell	Less than $10 initially	
Mobility		Cell reselection in idel stage	Cell switch in connection stage	
Phonetic ability		Nonsupport	Limited capacity	Weaker than FDD

h: INFLUENCE OF NETWORK DEPLOYMENT ON PRESENT NETWORK

The complexity and cost of network deployment are the main problems in decision-making process.

NB-IoT: for operators who have not deployed LTE FDD, the deployment of NB-IoT is closer to deployment of a brand new network, and it involves construction of new wireless network and core network, and adjustment to transmission structure. Meantime, if there is no ready-made idle spectrum, then adjustment (Standalone mode) to spectrum of present network (generally, it is GSM) is required, so the cost of implementation is higher. However, for operators who have already deployed LTE FDD, the existing equipment and spectrum can be utilized to a great extent in the deployment for NB-IoT, so the deployment is simpler. Regardless the system the construction relies on, an independent deployment of core network or equipment upgrade of present network is required.

eMTC: if eMTC network is deployed on the basis of 4G network, in the aspect of wireless network, the software of existing 4G networks can be upgraded, and in the aspect of core network, the deployment can be also realized through software upgrade.

i: SERVICE MODE

NB-IoT: the performance is superior in terms of coverage, power consumption, cost and connection count, but NB-IoT cannot meet service requirements such as mobility, medium rate and voice. Thus, it is suitable for LPWA applications which require low rate and low mobility.

eMTC: at present, eMTC performance is weaker than NB-IoT performance in aspects of coverage and module cost, but eMTC performance is superior to NB-IoT performance in aspects of peak rate, mobility and voice capability. Thus, eMTC is suitable for IoT application scenes with medium throughput rate and mobility or higher requirements for voice capability. Therefore, the application scenes of eMTC network are more abundant, and the relationship between application and human is more direct, i.e., the ARPU value is higher.

j: INTEGRATED PERFORMANCE

In general, both NB-IoT and eMTC have advantages and disadvantages. The detailed comparison of indices is shown in Table 7 [91]. Compared with LTE FDD eMTC and LTE TDD eMTC, NB-IoT has narrower band and lower peak rate, which means NB-IoT has better performance on ultra-low power consumption and low data rate services. Besides, NB-IoT supports massive connections, wide coverage and low cost.

B. COMPARISON BETWEEN NB-IoT AND OTHER WIRELESS COMMUNICATION TECHNOLOGIES

Due to the rapid growth of low-data-rate IoT services in an intelligent way, the LPWA technology becomes more and more popular in industry, and the market share is increasing gradually. According to the report of Hequan Wu in 2016 China Internet of Things Conference, the intelligent IoT applications can be classified into three categories based on data transmission rate requirements in 2020, Table 8.

1) HIGH DATA TRANSMISSION RATE

The data transmission rate is higher than 10 Mbps. The available access technologies are 3G, 4G and Wi-Fi. They are mainly used in television direct transmission, electronic healthcare, vehicle navigation system, vehicle entertainment system and etc. The expected market share for this kind of IoT applications is 10%;

2) MEDIUM DATA TRANSMISSION RATE

The data transmission rate is lower than 1 Mbps. The available access technologies are 2G and MTC/eMTC. Such applications include POS machine, smart home and M2M return

TABLE 8. **Distribution figure for connection technology of intelligent IoT in 2020.**

Global M2M/IoT connection distribution in 2020	Category	Network connection techniques	Fine-grained market opportunity
10 %	High data rate (>10Mbps), e.g. CCTV, eHealth	3G:HSPA/EVDO/TDS	Big profit margin for car navigation/entertainment system
		4G:LTE/LTE-A	
		WiFi 802.11 technologies	
30 %	Medium data rate (<1Mbps), e.g. POS, Smart Home, M2M Backhaul	2G:GPRS/CDMA2K1X	2G M2M could be replaced by MTC/eMTC techniques
		MTC/eMTC	
60 %	Low data rate (<100Kbps), e.g. Sensors, Meters, Tracking Logistics Smart Parking, Smart agriculture...	NB-IoT	Various application cases; Main market for LPWA; Market vacancy
		SigFox	
		LoRa	
		Short Distance wireless connection, e.g. Zigbee	

link. The expected market share for this kind of IoT applications is 30%. However, in the future 2G M2M will be gradually replaced by MTC/eMTC technology.

3) LOW DATA TRANSMISSION RATE

The data transmission rate is lower than 100 Kbps. The available access technologies are NB-IoT, SigFox, LoRa and short-range wireless communications like ZigBee. They are mainly applied in LPWA technologies including sensors, smart metering, goods tracking, logistics, parking and intelligent agriculture. The expected market share for this kind of IoT applications is 60%. However, there are still plenty of vacancies in corresponding market. Hence, NB-IoT will has a bright future.

The comparison between LPWAN represented by NB-IoT and many other communication modes from different perspectives is presented in Fig. 8. In Fig. 8(a), we classify them from the aspects of coverage area and data transmission rate. For short-range and high-bandwidth communication technologies such as Wi-Fi, the maximal coverage can reach 100 m and data transmission rate can be up to 100 Mbps. This kind of communication technology is appropriate for application with short range and high bandwidth requirements. In the case of short-range and low-data transmission rate communication technologies, such as Bluetooth and Zigbee, the maximal coverage area is also 100 m and data transmission rate can be up to 100 Kbps. On the other hand, for GSM the maximum coverage area is 10 km and the highest data transmission rate is 100 kbps. The long-range and low-data transmission rate communication technologies, such as LPWA, have coverage area of 10 km and the highest data transmission rate is 100 Kbps.

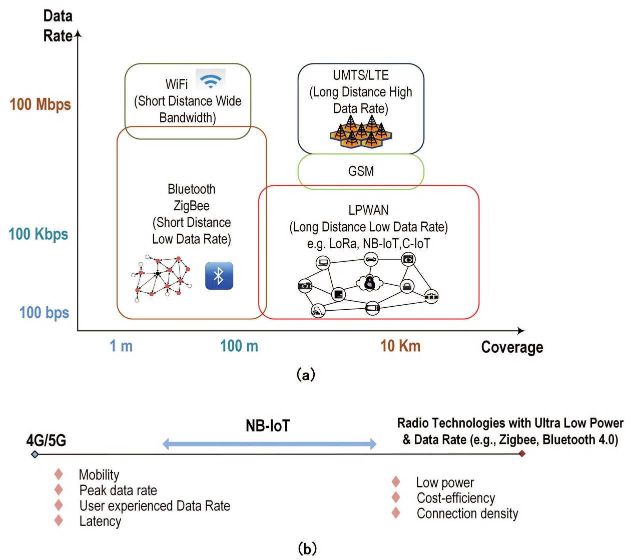

FIGURE 8. **Comparison between NB-IoT and other wireless communication technologies (a)Comparison of different wireless communication technologies; (b) NB-IoT design tradeoffs.**

The trade-off design of NB-IoT technology is presented in Fig. 8(b). It takes both advantages of 4G/5G technology, namely mobility, peak rate and user experienced data transmission rate, and advantages of low-power consumption wireless communication technologies (such as Zigbee technology), namely intensive transmission and low cost. The NB-IoT attempts to realize low-power consumption and wide-area wireless communication using a narrow-band technology.

In Fig. 9, we compare 8 performances including price, latency, security, availability, data transmission rate, energy

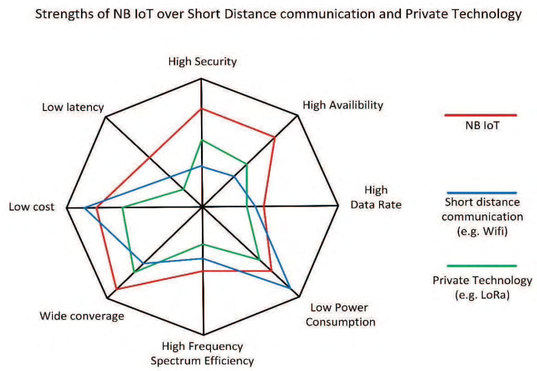

FIGURE 9. Performance comparison of NB-IoT, Wi-Fi and LoRa.

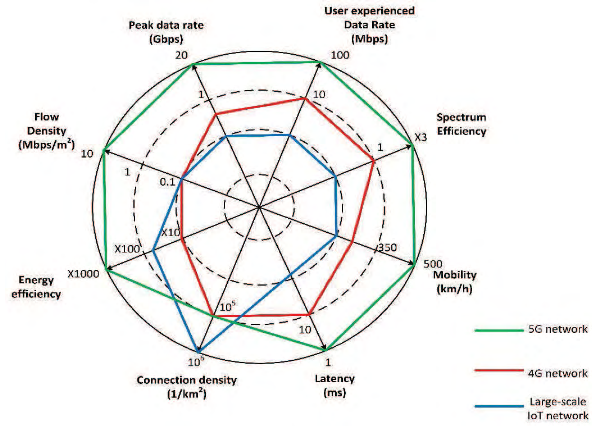

FIGURE 10. Performance comparison of LPWAN, 4G and 5G networks.

TABLE 9. Comparison between NB-IoT and LoRa.

Item	NB-IoT	LoRa
Power consumption	Low(10 years battery life)	Low(10 years battery life)
Cost	Low	Lower than NB-IoT
Safety	Telecom level security	Slight interference
Accuracy rate	High	High
Coverage	<25 km (resend supported)	<11 km
Deployment	Rebuild supported based on LTE FDD or GSM	Inconvenience

consumption, spectrum efficiency and coverage area among NB-IoT, short distance communication technology (such as Wi-Fi) and private technology (such as LoRa). As it is shown in Fig. 9, both short distance communication technology and private technology have their own merits and defects. However, NB-IoT has better performance. For instance, NB-IoT is superior to other two technologies in aspects of low latency, high security, high availability, high data transmission rate, high spectrum efficiency and wide coverage area. Moreover, regarding low price and low energy consumption, the performance of NB-IoT is between the performances of short distance communication technology and private technology. In brief, Fig. 9 shows that NB-IoT would provide better communication mode compared to other two technologies.

In allusion to WAN communication technology, we conducted a simple comparison between NB-IoT and LoRa, and results are presented in Table 9.

Table 9 shows that NB-IoT can be prospering in operator-level network in the future. Moreover, the NB-IoT could bring us many network solutions providing wide coverage area, large connection density and low cost IoT. In addition, because of rapid and flexible deployment, LoRa could be also realized in smart cities, exclusive industrial and corporate applications. However, we can ensure that these two LPWA technologies are complementary in commercial use.

Starting from the evolution of mobile communications, we compared the performance of LPWAN and mobile communication network (represented by 4G and 5G) from 8 aspects: peak data rate, user experienced data rate, spectrum efficiency, mobility, latency, connection density, energy efficiency and flow density. As it is shown in Fig. 10, LPWAN is superior to 4G/5G network in connection density but not as good as them in other aspects. The superiority of 5G network is especially obvious. Further, the energy efficiency of LPWAN is higher than energy efficiency of 4G network but lower than energy efficiency of 5G network. Fig. 10 shows that LPWAN can be applied to applications which require low energy consumption, low data transmission rate and large connection density. Another big advantage of LPWAN, which is not marked in the diagram, is its low cost. Thus, LPWAN, represented by NB-IoT, has a great potential in IoT field.

Furthermore, compared to the advanced LTE IoT technology, the performance of LTE-M (LTE-Machine to Machine) has been greatly improved, in contrast with that of 1G, 2G and 3G technologies. The LTE-M occupies only 1-MHz bandwidth, while NB-IoT performs better with 200-kHz bandwidth. However, both LTE-M and NB-IoT largely reduce 20-MHz bandwidth used in the past, but their data transmission rate correspondingly decreases from 1 Mbps to 200 kbps. Accordingly, because of lower band with occupancy rate, NB-IoT is more convenient for promotion and deployment.

Besides, low power consumption and wide coverage can be achieved by NB-IoT, whose coverage area is currently up to 20 km. In order to achieve target coverage, it is generally suggested that NB-IoT should be realized at lower frequency band, at 700 MHz, 800 MHz, 900 MHz or at other frequency bands less than 1 GHz. In addition, we must note that coverage involves not only distance but also penetrability. In that aspect, it is emphasized that NB-IoT has better penetrability than 2G GSM. Namely, its signal strength is 20 dB higher. Therefore, even in indoor environment, we can obtain high quality communication.

The current channel bandwidth of IEEE 802.11ah is 1/2/4/8/16 MHz, similar to the LTE-M bandwidth. Generally, Zigbee requires channel bandwidth of 2-5 MHz. The exception is Zigbee at 868 MHz in European region that occupies 800 kHz bandwidth, which is inferior to NB-IoT bandwidth. Moreover, the transmission distance of 11 Ah still needs to be tested. The current distance is only 1 km, which is inferior to NB-IoT distance, which is from several kilometerss to 20 km.

In aspect of cost, Huawei thinks that the prices of NB-IoT chipset and module composed of chipset should be about 1$ and 3-5$, respectively. Besides, due to the power consumption requirement, the battery must provide continuously operation for 10 years without replacement.

According to current proposals, LTE or LTE-M2M base station must be able to support 100,000 terminals or at least 50,000 terminals. Actually, similar objective has been also proposed by 5G. In current stage, the requirement for 5G is 1,000,000 terminals per square kilometer, i.e., one terminal per square meter. In contrast, the NB-IoT requirement is still not strict.

Moreover, we compared relevant applications of three technologies. The Category 0 formulated in R12 of 3GPP is mainly used for wearable electronics and energy management, or to be more specific, for fitness-based smart watches and household electricity consumption control. However, the LTE-M with 1-MHz bandwidth is expected to be used for object tracking (including pet lost, stolen bicycle and other cases), metering of utility services, on-line health diagnosis and monitoring, and municipal infrastructure construction (such as recording of slot machine for parking and street lamp management). However, NB-IoT is partial to industrial applications such as environment monitoring and smart building.

In fact, NB-IoT can compete many current and future communication technologies. Moreover, there are Sub-1GHz transmission plans formulated and pushed by chip corporations; for instance, the plan for smart grid and charging station for electric vehicles based on Zigbee with NAN (Neighborhood Area Network) as a localization technology [9], IEEE 802.11ah, Wi-SUN, Wireless M-Bus, and etc.

III. INTELLIGENT APPLICATION OF NB-IoT

A. APPLICATION SCENES OF NB-IoT

Due to its characteristics, the NB-IoT technology can meet requirements of low data transmission rate services with low power consumption/long standby time, wide coverage and large capacity, but it is difficult to support high mobility.Thus, NB-IoT is better fit for static, low latency sensitivity, discontinuous movement or real-time data transmission services. The following services can be considered:

- Autonomous exception reporting services, including smoke detector smart metering notice and etc. Their uplink data size requirement is quite small (at level of 10 bytes) and transmission cycle is mostly a year or month.
- Autonomous periodical reporting services, whose uplink data size requirement is relatively small (at level of 100 bytes) and the transmission cycle is a day or an hour. Typical applications include measurement report for intelligent utility services (such as electricity, water and gas), intelligent agriculture and intelligent environment.
- Network command services. This type of services includes startup/shutting off, sending uplink report, metering requirement and etc. Different from autonomous exception reporting service, its downlink data size is quite small (at level of 10 bytes) and the transmission cycle is usually a day or an hour.
- Software upgrading service. The software patch/ upgrading uplink and downlink data sizes are relatively large (at level of 1,000 bytes), and transmission cycle is usually a day or an hour.

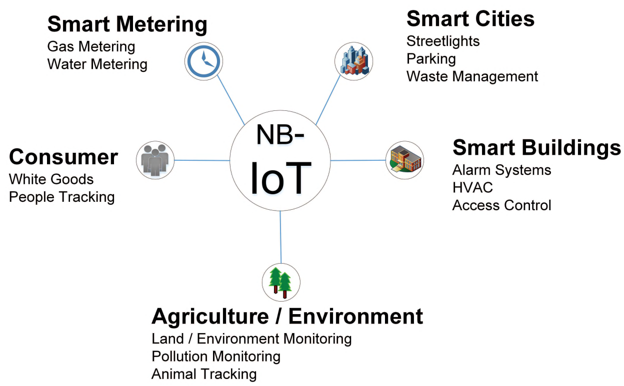

FIGURE 11. Intelligent application of NB-IoT.

As it is shown in Fig. 11, the specific application scenes of NB-IoT can be summarized into smart cities, smart buildings, intelligent environment monitoring, intelligent user services and smart metering. Thereinto, intelligent user services include wearable devices, smart home/white goods, intelligent dustbin, people tracking and etc. The intelligent environment monitoring includes intelligent agriculture, pollution monitoring, water quality monitoring, soil detection, and etc [92], [93].

Smart city aims to make interconnection among public facilities such as vehicles, roads, street lamps, parking space, well lid, dustbin, electricity meter, water meter, gas meter and heat meter, in order to realize intelligent municipal management (such as intelligent management of infrastructure such as water, electricity and gas in the city), intelligent traffic management (such as traffic flow control, road condition analysis, emergency disposal and smart parking, which will assist the realization of 5G Internet of Vehicles), and etc. The most important feature of smart city realization is communication coverage of IoT network [94], [95]. With the gradual establishment of NB-IoT standard, it is easy to form a scale effect using the experience of operators in constructing a large scale network in cities. An important feature of NB-IoT is deep and wide coverage. Even the basement and parking lot should be covered. Thus, various problems in industry from the past are smoothly solved. The challenge of

NB-IoT is the matching and reconstructing traffic operation mode of operators. In 2017, Lu *et al.* [96] firstly proposed a NB-IoT platform to monitor the unmanned aerial vehicles in smart cities, which prevents the UAVs' accidentally falling effectively.

B. INSTANCES FOR INTELLIGENT APPLICATION OF NB-IoT

The functional verification of NB-IoT-based smart metering, intelligent parking and intelligent dustbin service was conducted collectively by Huawei and many global operators in China, Germany, Spain, United Arab Emirates and other countries. The first pre-commercial trial of pre-standard NB-IoT was completed by Vodafone and Huawei at the end of 2015 in Spain, which successfully integrated NB-IoT technology into existing mobile network of Vodafone. Namely, NB-IoT message was sent to IoT module of water meter. Usually, water meter is placed in hidden environment such as closet, and connection to power source is not available for water meter. In such conditions, NB-IoT effectively solves the problems of poor coverage and power consumption.

Recently, the commercial test and cooperation between Huawei and China Unicom/China Mobile have also been started. Thereinto, at the MWC held in 2015, the first experiment application, the intelligent parking based on commercial network was deployed by Huawei, China Unicom, and Shanghai Branch [97]. Since the standardization for NB-IoT had not been completed at that time, the pre-commercial services involved non-standard schemes. However, the difference should not be great in comparison to the future standard for NB-IoT services. Several actual applications of NB-IoT are as below:

(1) NB-IoT intelligent parking solution by Huawei and China Unicom. Based on NB-IoT module of Huawei, this intelligent parking system is able to realize functions such as parking space reservation and subletting. The low power consumption and high penetrability make this scheme more reliable. Currently, this parking system is used in the pre-commercial service in Shanghai Disney Resort.

(2) Smart well lid by Zhongxing Telecom and China Mobile. In this scheme, the state of well lids is monitored in all directions. It can realize real time monitoring regardless the well lid is opened or moved. The advantages of this application based on NB-IoT include low cost, wide coverage, low power, big connection and so on, and it can effectively enhance the coverage area of intelligent well lid monitoring system, eliminate dead angles, and reduce construction and maintenance cost.

(3) Environment monitoring application by China Mobile, Ericsson and Intel. With the latest NB-IoT chip (XMM7115) of Intel, this application is able to conduct real-time monitoring for environment indices such as PM value, temperature, humidity, photo-esthetic brightness and etc.

IV. SECURITY REQUIREMENTS OF NB-IoT

The security requirements of NB-IoT are similar to those of traditional IoT, Fig. 12 [98]. However, there are many differences, which mainly relate to IoT hardware equipment with low power consumption, network communication mode, and actual service requirements. For instance, the terminal system of traditional IoT generally has strong computing power, complicated network transmission protocol and adopts stricter security reinforcement plan; also, power consumption is usually high and frequent charging is required. On the other hand, a low-power IoT equipment is featured by low power consumption, low computing power and non-frequent charging, which also means that security issues are more likely to pose a threat to terminals. In addition, a simple resource consumption may cause the state of denial of service. Furthermore, in actual deployment, the number of low-power consumption IoT terminal devices is far larger than in traditional IoT [99]. As a result, any tiny security vulnerability may produce much more large security accidents because the terminal's embedded system is more simpler and more lightweight, thus it is much easier for attacker to master full information on system.

The following analysis presents the security requirements of NB-IoT aiming to the 3-layer architecture consisted of perception layer, transmission layer and application layer.

A. PERCEPTION LAYER

The perception layer is the bottom layer of NB-IoT which represents the foundation of upper layers of architecture and services. Similar to the common IoT perception layer, the perception layer of NB-IoT tends to be under both passive and active attacks. The passive attack means that the attacker only steals the information without making any modification.The main methods include eavesdropping, traffic analysis and so on. As the transmission of NB-IoT relies on open wireless network, attackers may obtain information on NB-IoT terminals with methods such as stealing data link and analyzing traffic features with the aim to conduct a series of subsequent attacks.

Different from passive attacks, active attacks include integrity damage and falsification of information, therefore, the extent of injury brought by active attack to NB-IoT network is far larger than by passive attack. At present, the main active attack methods include node replication attack, node capture attack, message tampering attack, etc. For instance, in typical application of NB-IoT, the "smart meters", if the attacker captures user's NB-IoT terminal, then the attacker can arbitrarily modify and falsify the meter readings, which directly affect the user's vital interests.

In the above-mentioned attacks, the cryptographic algorithms such as data encryption, identity authentication and integrity verifying can be adopted for prevention. The frequently-used cryptology mechanisms include random key pre-allocation mechanism, deterministic key pre-allocation mechanism, and password mechanism based on identity. The service life of battery in NB-IoT equipment can reach 10 years in theory. Since the throughput rate for perceiving data at NB-IoT node is small, for the purpose of safety, a lightweight password (such as stream cipher and block

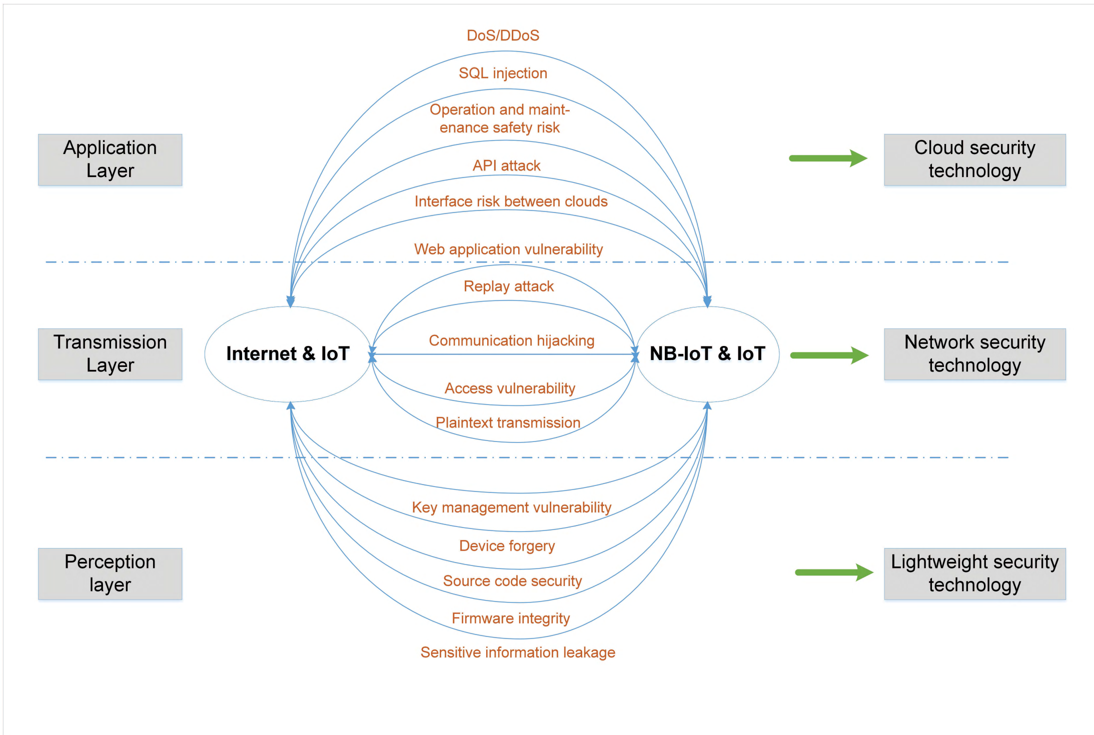

FIGURE 12. **The similarity between NB-IoT and traditional IoT in terms of security requirements.**

cipher) should be deployed in perception layer to reduce computation load at terminals and to prolong service life of battery.

Different from perception layer in traditional IoT, here the perception layer node can directly communicate with the base station in the cell, thus potential routing security problems during networking are avoided [100]. On the other hand, the identity authentication between nodes in perception layer of NB-IoT and base station in the cell should be bidirectional, i.e., the access authentication should be conducted by the base station to the certain perception node of NB-IoT, and it should be also conducted by the NB-IoT node to the base station in current cell in order to prevent security threat that could be brought by pseudo base station.

B. TRANSMISSION LAYER

In contrast to the transmission layer in traditional IoT, NB-IoT changes the complicated network deployment wherein relay gateway collects information and then feeds back to base station. Therefore, many problems such as multi-network networking, high cost and high-capacity battery are solved. One network for a whole city can bring convenience for maintenance and management and advantages such as easily addressing and installing through separating from property service. However, new security threats are also present:

- Access to high-capacity NB-IoT terminals

One sector of NB-IoT is able to support connection to about 100,000 terminals. The main challenge is to conduct efficient identity authentication and access control for these massive real-time high-capacity connections in order to avoid injection of false information by malicious node.

- Open network environment

The communication between perception of NB-IoT and transmission layer is totally through wireless channel. The intrinsic vulnerability of wireless network brings potential risks to the system. Namely, attacker could transmit interference signal to cause communication outage. In addition, as there is a large amount of nodes in a single sector, attacker could sponsor the Denial of Service (DoS) attack with nodes controlled by him, thus he could influence the network performance.

The solution of above problems is to introduce efficient end-to-end authentication mechanism and key agreement mechanism, thus to provide confidentiality and integrity protection of data transmission as well as information legality identification. At present, there are relevant transmission security standards for both computer network and LTE mobile communications, such as IPSEC, SSL and AKA. However, the main problem is realization of these technologies in NB-IoT system through efficiency optimization.

On the other hand, the perfect intrusion detection and protection mechanisms should be established in order to detect illegal information injected by malicious nodes. To be specific, firstly, a series of behavior profile configurations should be established and maintained for certain kind of NB-IoT nodes. These configurations should certainly describe the behavior characteristics of corresponding nodes during normal operation. When the difference between current activity of one NB-IoT node and its past activities exceeds the threshold of items in profile configuration, this current activity will be viewed as abnormity or intrusion behavior; and the system should conduct timely interception and correction to avoid adverse impact by various intrusions/attacks to network performance.

C. APPLICATION LAYER

The target of application layer of NB-IoT is to store, analyze and manage data effectively. After perception layer and transmission layer, a large amount of data converges in application layer. Then, massive resources are formed to provide data support for various applications. Compared with application layer of traditional IoT network, the application layer of NB-IoT carries larger amount of data. The main security requirements are as follows:

- Identification and processing of massive heterogeneous data

Due to diversity of NB-IoT applications, the data converged in application is heterogeneous which increases complexity of data processing. Therefore, the efficient identification and management of these data with existing computing resources becomes the core problem of NB-IoT application layer. In addition, real-time disaster tolerance, fault tolerance and back-up are also questions worthy of consideration. The effective operation of NB-IoT services should be guaranteed as far as possible in various extreme cases.

- Integrity and authentication of data

The data converged in application layer come from perception and transmission layers. The only exception occurs during collection and transmission, wherein the integrity of data is subjected to varying degrees of damage. Besides, an illegal operation by insiders on data would also bring data integrity loss. Thus, data usage in application layer might be influenced. The solution of these security problems lies in establishment of efficient data integrity verification and synchronization mechanisms. In addition, data de-duplication technology, data self-destruct technology, data flow auditing technology and others technologies are also necessary to guarantee the security of data during storage and transmission processes in all directions.

- Access control of data

There is a large amount of user groups in NB-IoT. The access and operating authorities for different users on data are different. The corresponding authorities for different levels of users should be set up to make users conduct controlled information sharing. Currently, the access control mechanisms for data are mainly mandatory access control mechanism, discretionary access control mechanism, role-based access control mechanism and attribute-based access control mechanism. Different access control measures should be taken as per difference in privacy of application scenes.

V. CONCLUSION

In this paper, we provide the background and state-of-the-art of NB-IoT. Firstly, we introduce the general background of NB-IoT and give a brief review of NB-IoT development history and standardization. Then, we introduce the features, basic theory and key technologies of NB-IoT, such as connection analysis, latency analysis, coverage enhancement mechanism, etc. Afterwards, we focus on the differences between NB-IoT and several communication technologies, including eMTC and other wireless communication technologies. With the aim to introduce the intelligent application of NB-IoT, we list some specific application scenes and give the corresponding examples. Finally, we review the security requirements of NB-IoT from three levels, namely perception layer, transmission layer and application layer. These discussions aim to provide the comprehensive overview and big-picture of NB-IoT to readers of this exciting area.

There can be many future research directions for this study. We will continue to research a visible network model, which is able to visually reflect the operation situation of NB-IoT network. Such model should complete the construction of each functional module and realize link level open-type simulation and verification platform of NB-IoT. Furthermore, based on that NB-IoT network model, we will test and verify the characteristics of NB-IoT, and accumulate experiences for the large-scale deployment in the future real world.

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