Narrowband Internet of Things: Simulation and Modeling

Yiming Miao, Wei Li, Daxin Tian, *Senior Member, IEEE*, M. Shamim Hossain, *Senior Member, IEEE*, and Mohammed F. Alhamid, *Member, IEEE*

***Abstract*—As a new type of low power wide area (LPWA) technology, the narrowband Internet of Things (NB-IoT) technology supports wide coverage and low bitrate services, thus it has a great potential to be the future commercial technology of LPWA network. Therefore, it has attracted attention of both academia and industry. In this paper, we present the NB-IoT development, and main characteristics and design objectives of NB-IoT according to 3GPP R13. In addition, we provide the review of related literatures about NB-IoT modeling and algorithm analysis. And we explain current problems of NB-IoT system-level modeling based on visualized simulation platform. Moreover, this paper is devoted to the construction of the NB-IoT model based on OPNET and the verification of its characteristics, such as wide coverage and high channel utilization. This paper mainly considers NB-IoT model design and realization in terms of NB-IoT physical layer characteristics. We summarize the correlated characteristics of NB-IoT uplink and downlink. Then we design and construct the NB-IoT model based on Long Term Evolution (LTE) network. Lastly, we use the constructed NB-IoT model for simulations and conduct an experiment on it using the LTE network with channel bandwidths of 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. The simulation results have verified the performance of NB-IoT, wherein uplink time delay is lower than 10 s, channel utilization is higher than that of LTE network, and coverage area is larger than LTE network.**

***Index Terms*—Internet of Things (IoT), Long Term Evolution (LTE), low power wide area network (LPWAN), narrowband IoT (NB-IoT), OPNET.**

I. INTRODUCTION

NOWADAYS, due to continuous development of Internet of Things (IoT), the IoT communication technology is increasingly mature [1]. IoT has achieved significant improvement in big data processing [2], heterogeneity [3], and performance [4]. The IoT technologies can be separated into two categories from the aspect of communication distance: 1) short-haul communication technologies (such as Zigbee, Wi-Fi, Bluetooth, Z-wave, etc.) and 2) low power wide area (LPWA) technologies desired by LPWA machine-to-machine networks: key techniques and prototype [5]–[7]. Among them, the LPWA technologies have a significant development. The LPWA technologies can be separated into two types by whether the frequency spectrum is authorized or not: technologies that work in unauthorized frequency band (such as Lora, Sigfox, and etc.) are mostly nonstandard and realized as user-defined, and technologies that work in authorized frequency band, including GSM, code division multiple access (CDMA), WCDMA and other relatively mature 2G/3G cellular communication technologies, as well as the Long Term Evolution (LTE) and its evolution technologies, are gradually deployed and applied at present and support different categories of devices, also these technologies have almost made standard definition of 3GPP (mainly formulating the relevant standards for GSM, WCDMA, LTE and its evolution technologies) and 3GPP2 (mainly formulating the relevant standards for CDMA) and other international standard organizations [8].

The narrowband IoT (NB-IoT) is a new type of LPWA technology released by 3GPP intended for sensing and data collection applications, such as intelligent electric meters, environment supervision, and etc. [9], [10]. It has many advantages, such as massive connections, ultralow power consumption, wide area and deep coverage, intertriggering between signaling and data, and etc. [11]–[14]. Meanwhile, it has a good communication network support [15]. Therefore, it has a great potential for future implementation. The main characteristics of NB-IoT are presented in detail as shown in Fig. 1. The NB-IoT can satisfy the requirements of nonlatency-sensitive and low-bitrate applications (time delay of uplink can be extended to more than 10 s, and uplink or downlink for a single user are supported at 160 bit/s at least), which are coverage enhancement (coverage capacity is increased 20 dB), ultralow power consumption (a 5-Wh batter can be used by one terminal for 10 years), and massive terminal access (a single sector can supports 50 000 connections) at transmission bandwidth of 180 kHz [16].

The NB-IoT adopts current LTE specifications, including numerologies, downlink orthogonal frequency-division multiple-access (OFDMA), uplink single-carrier frequency-division multiple-access (SC-FDMA), channel coding, rate matching, interleaving, etc. [17]. The physical layer, air interface of high layer, access network, and core network are

Manuscript received June 1, 2017; revised July 14, 2017, July 24, 2017, and July 28, 2017; accepted July 29, 2017. Date of publication August 14, 2017; date of current version August 9, 2018. This work was supported by the Deanship of Scientific Research at King Saud University, Riyadh, Saudi Arabia, for funding this research group under Grant RG-1437-042. *(Corresponding author: Daxin Tian.)*

Y. Miao and W. Li are with the Wuhan National Laboratory for Optoelectronics and with School of Computer Science and Technology, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: yimingmiao@hust.edu.cn; weili.epic@qq.com).

D. Tian is with the Beijing Advanced Innovation Center for Big Data and Brain Computing, School of Transportation Science and Engineering, Beihang University, Beijing 100191, China (e-mail: dtian@buaa.edu.cn).

M. S. Hossain and M. F. Alhamid are with the Department of Software Engineering, College of Computer and Information Sciences, King Saud University, Riyadh 11543, Saudi Arabia (e-mail: mshossain@ksu.edu.sa; mohalhamid@ksu.edu.sa).

Digital Object Identifier 10.1109/JIOT.2017.2739181

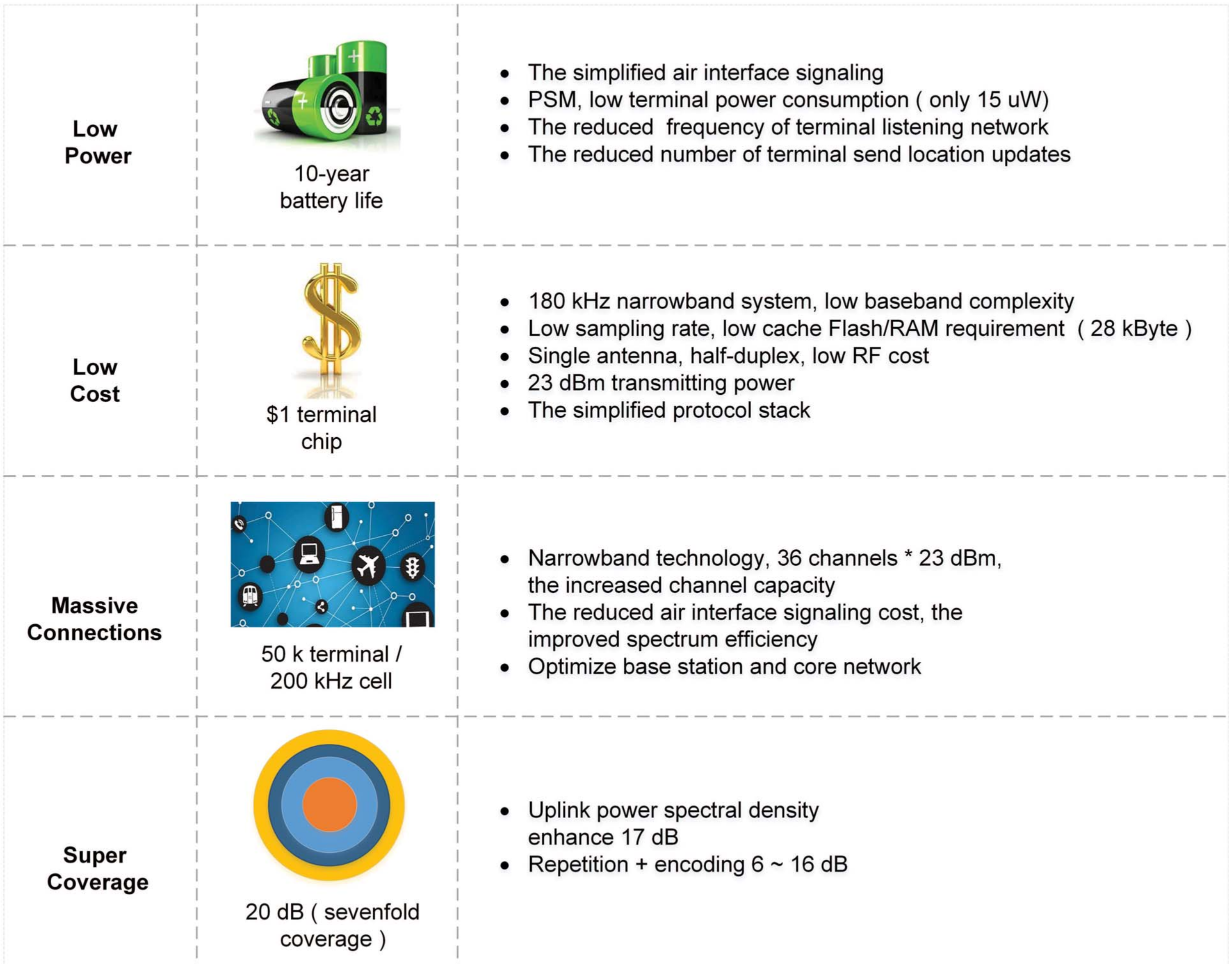


Fig. 1. Main features of NB-IoT.

improved and optimized to satisfy above-mentioned requirements [18]–[20]. Therefore, the same hardware facility can be used repeatedly, and the frequency spectrum resources can also be shared without any problem on compatibility. This allows us to use current infrastructure for fast low-cost deployment of NB-IoT. In relatively new equipment station, the NB-IoT can be implemented through software upgrade. However, old devices may be unable to support LTE and NB-IoT simultaneously, therefore hardware upgrade is required [21]. In this case, if current unit stations are upgraded to NB-IoT step by step, the NB-IoT implementation can be also made stage by stage without simultaneous hardware upgrade at all stations [22], [23]. Therefore, the NB-IoT can be upgraded gradually until all stations are fully upgraded. Moreover, the NB-IoT module can be deployed into the LTE core network step by step, which will fully support all network services, such as identity verification, security, strategy, tracking, charging, and etc., and it will significantly reduce the developing time of a full-scale network [24]. Furthermore, suppliers of current LTE device and software will spend much less time to develop NB-loT devices. The normalization stage of the 3GPP IoT working project has been started in September 2015. The core specification has been completed in June 2016. The commercial launching of NB-IoT produces and services is expected to be completed in 2017 [25].

The main targets of all researchers are developing NB-IoT model and realizing the expected requirements of NB-IoT. With the aim to verify the possibility of deploying of NB-IoT network in many real-world infrastructure, this paper uses OPNET network simulation platform to build the NB-IoT network architecture. Based on the LTE infrastructure, we design and realize the physical layer of NB-IoT. We also compare performances of NB-IoT network and LTE network with different channel bandwidths for coverage range, signal channel utilization and other basic performances, and verify wide coverage, high channel utilization, and other characteristics of NB-IoT.

This paper is organized as follows. Section II provides the related research work. Section III introduces the physical layer of NB-IoT. Section IV shows the envisioned NB-IoT architecture, provides simulation setup, and discusses simulation results. Finally, Section V concludes this paper.

II. Related Work

Nowadays, due to evolution of IoT, the NB-IOT becomes a newly developing hot research topic, and it has been widely implemented in various fields, such as healthcare [26]–[28], data center [29], etc. The main challenge is to bring four major superiorities of NB-IoT, namely long battery life, low cost, large capacity, and wide coverage, into real applications.

Aiming at the NB-IoT system for M2M communication, some related literature introduces physical properties and design objectives of NB-IoT [30]–[32]. Mangalvedhe *et al.* [33] used current LTE infrastructure to develop and research NB-IoT, as well as to discuss whether the partial deployment of NB-IoT is practicable. With the aim to analyze further coverage performance of NB-IoT, Adhikary *et al.* [34] conducted a detailed analysis on coverage performance of NB-IoT under the assumption that NB-IoT infrastructure has already been deployed, and in comparison with current LTE technology, a coverage enhancement of 20 dB was achieved. Moreover, Lauridsen *et al.* [35] made a contrastive analysis on coverage and performance of LTE-M and NB-IoT for specific scene, the suburban district. It was found that for deeply indoor users, the coverage of NB-IoT is obviously better than coverage of LTE-M.

Recently, new algorithms and protocols have been applied to NB-IoT in order to improve it. Lin *et al.* [36] developed the receiver algorithm for NB-IoT physical random access channel (NPRACH) detection and arrival time estimation. They presented simulation results for NPRACH, including detection rate, false alarm rate, and estimated accuracy of arrival time, to highlight the overall potential of NB-IoT system. In addition, Ali and Hamouda [37] proposed the algorithm for NB-IoT cell search and initial synchronization, and simulation result indicated that proposed method can provide the required performance even for a very low SNR. From the perspective of energy-saving, Kroll *et al.* [38] realized hardware (detector) for maximum probability cross-correlation detection of initial timing collection of NB-IoT devices. The mean detection delay of detector was two times lower than the one obtained by autocorrelation method, which reduced the energy required by each timing collection for 34%. Another approach was proposed in [39] and [40] that exploits agent-based modeling and simulation to analyze performance of IoT systems. The approach is based on ACOSO [41] for the modeling phase and OMNET++ for the simulation phase. Furthermore, Liu *et al.* [42], [43] presented two novel resource negotiation schemes bridging between dynamic sensing tasks and heterogeneous IoT sensors, particularly to control the device duty cycles for energy saving.

However, above-mentioned works have not provided a visible network model. And they are unable to reflect the operation of NB-IoT network visually. On the other hand, this paper realizes an NB-IoT link level open-type simulation and verification platform based on OPNET, completes the construction of each functional module, tests, and verifies the characteristics of NB-IoT physical layer, and accumulates experiences for a large-scale implementation in future real-world applications.

III. Characteristics of NB-IoT Physical Layer

The NB-IoT system supports three deployment modes: 1) independent deployment mode; 2) guard-band deployment mode; and 3) in-band deployment mode (Fig. 2).

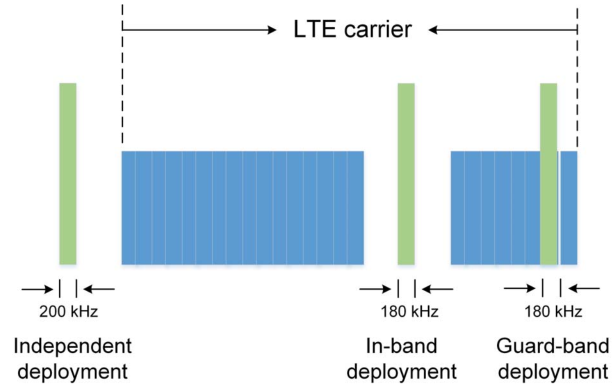


Fig. 2. Three deployment modes supported by NB-IoT.

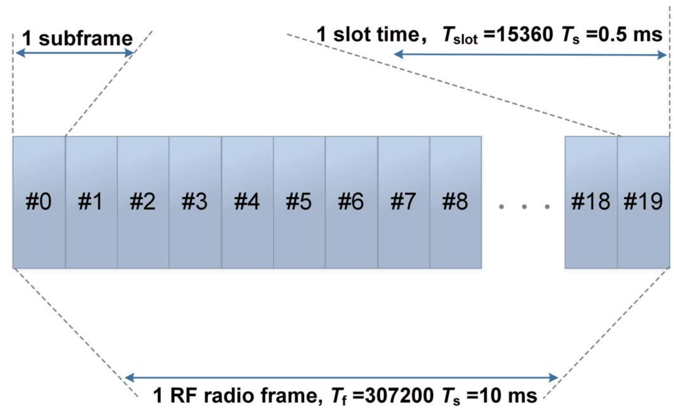


Fig. 3. NB-IoT frame structure (15 kHz subcarrier spacing of uplink and downlink).

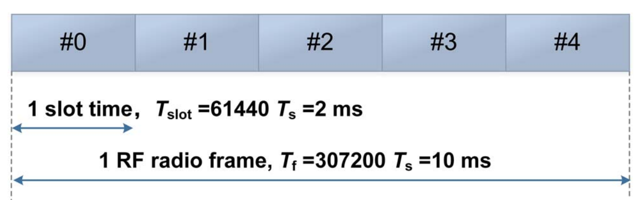


Fig. 4. NB-IoT frame structure (3.75 kHz subcarrier spacing of uplink).

- Independent deployment mode utilizes frequency spectrum occupied by current GSM/EDGE wireless access network system to replace the existing single or multiple GSM carrier wave.
- Guard-band deployment mode utilizes the resource blocks which are not used for current LTE carrier wave guard band.
- In-band deployment mode utilizes the resources blocks of LTE carrier wave.

A. NB-IoT Downlink

The downlink transmission bandwidth of NB-IoT system is 180 kHz. It adopts the 15-kHz subcarrier spacing, the same as current LTE. The downlink multiaccess mode (OFDMA technology), frame structure (in time domain, ten 1-ms subframes constitute one radio frame, but each subframe in the frequency domain contains 12 continuous subcarrier waves),

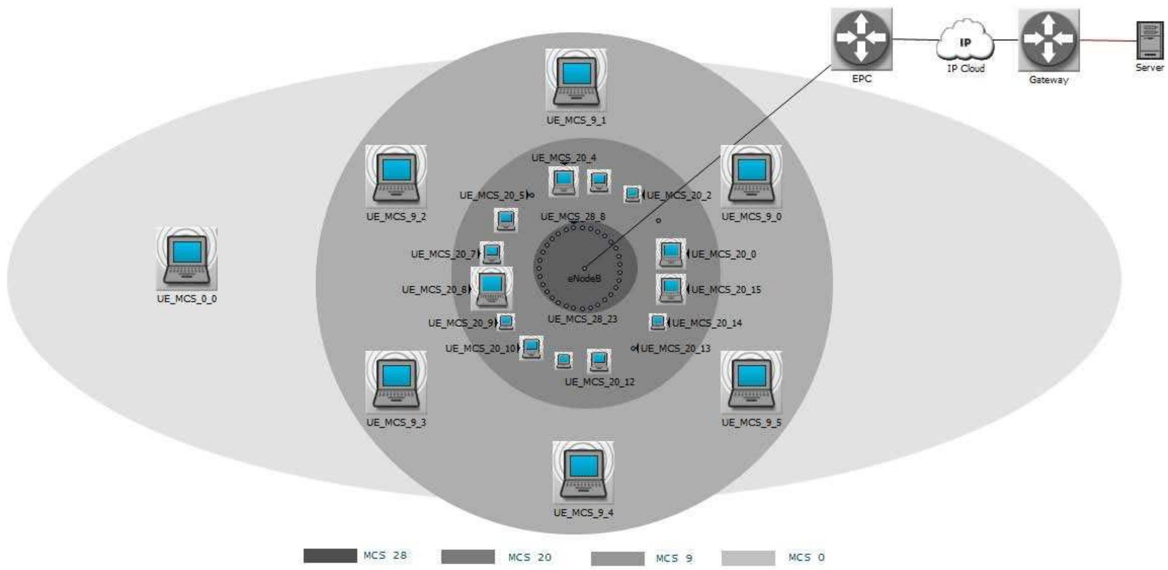


Fig. 5. NB-IoT network architecture.

and physical resource unit follow design of current LTE as much as possible [44].

Aiming at feature of 180-kHz downlink transmission bandwidth and requirement for coverage enhancement, NB-IoT reduces downlink physical channel, and redesigns part of downlink physical channel, synchronizing signal, and reference signal, including: narrowband physical broadcast channel, narrowband physical downlink sharing channel (NPDSCH), narrowband physical downlink control channel (NPDCCH), narrowband master sync signal (NPSS)/narrowband subsidiary master sync signal (NSSS), and narrowband reference signal (NRS). Further, it does not support physical control format indicator channel (the starting OFDM symbols in subframe follow the operation mode and the instructions of signal in system information block 1) and physical mixed retransmission indicator channel, but it adopts uplink authorization to make the retransmission of narrowband physical uplink shared channel (NPUSCH). Furthermore, it introduces retransmission mechanism in downlink physical channel and improves demodulation threshold through the diversity gain and merged gain of retransmission, which can enhance downlink coverage.

In order to solve the resource blocking problem of enhanced coverage, the periodic downlink transmission interval is introduced. For instance, for the requirement of maximal 20-dB coverage improvement in the in-band operation mode, the NPDCCH needs about 200–350 ms of retransmission, while NPDSCH needs about 1200–1900 ms of retransmission. If the resources are continuously occupied by NPDCCH and NPDSCH, the uplink/downlink authorization or downlink packets traffic transmission of other terminals will be blocked.

TABLE I
MCS INDEX

MCS Index (I_{MCS})	Modulation	TBS Index (I_{TBS})
0	QPSK	0
1	QPSK	1
2	QPSK	2
3	QPSK	3
4	QPSK	4
5	QPSK	5
6	QPSK	6
7	QPSK	7
8	QPSK	8
9	QPSK	9
10	16QAM	9
11	16QAM	10
12	16QAM	11
13	16QAM	12
14	16QAM	13
15	16QAM	14
16	16QAM	15
17	64QAM	15
18	64QAM	16
19	64QAM	17
20	64QAM	18
21	64QAM	19
22	64QAM	20
23	64QAM	21
24	64QAM	22
25	64QAM	23
26	64QAM	24
27	64QAM	25
28	64QAM	26

B. NB-IoT Uplink

The uplink transmission bandwidth of NB-IoT system is also 180 kHz, and it supports two subcarrier spacings, 3.75 and 15 kHz. In coverage enhancement scene, 3.75-kHz subcarrier spacing provides larger system capacity than 15-kHz subcarrier spacing. However, in the in-band operation mode

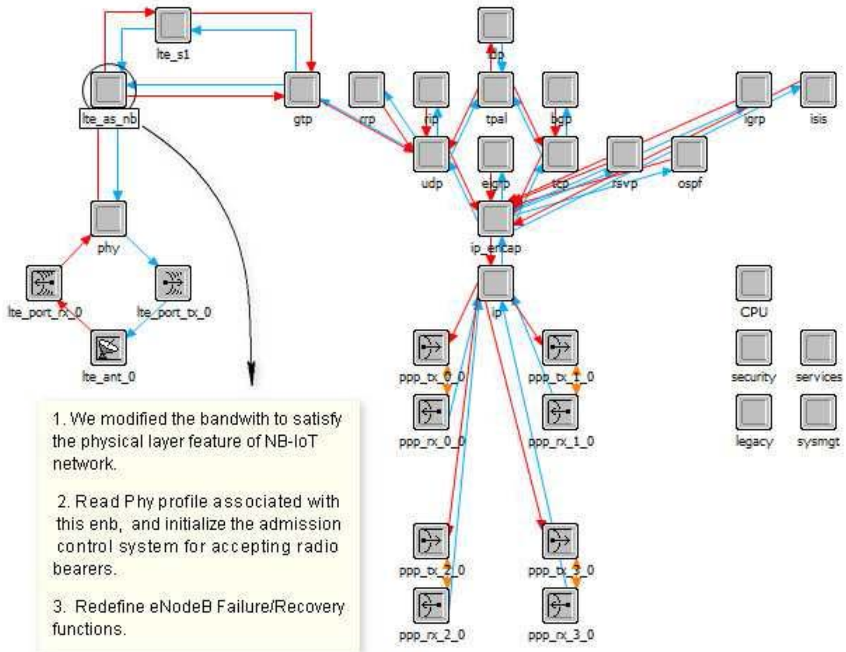


Fig. 6. Processor model of a simulated NB-IoT eNodeB.

scene, 15-kHz subcarrier spacing has better LTE compatibility than 3.75-kHz subcarrier spacing.

The uplink supports both single subcarrier and multiple subcarrier transmissions. In single subcarrier transmission, the subcarrier spacing can be 3.75 or 15 kHz; while in multiple subcarrier transmission, the subcarrier spacing of 15 kHz is adopted. The terminals need to support both single subcarrier and multiple subcarrier transmissions for easier selection of suitable mode by base station (for instance, through the msg1 or msg3 instruction of random access process). For both single subcarrier and multiple subcarrier, the uplink uses the multiple access technology based on the SC-FDMA. For 15-kHz subcarrier spacing, the NB-IoT uplink frame structure (frame size and time slot length) is the same as LTE network, as shown in Fig. 3. For 3.75-kHz subcarrier spacing, as shown in Fig. 4, the NB-IoT has a newly defined narrowband time slot of 2 ms. Namely, one radio frame contains five narrowband time slots [45]–[47], and each narrowband time slot contains seven symbols and reserves guard interval between each time slot for minimizing the confliction between NB-IoT symbol and LTE sounding reference signal [48], [49].

The NB-IoT network changes uplink physical channel, and redesigns part of uplink physical channel, including NPRACH and NPUSCH. But it does not support physical uplink control channel [50].

With the aim to enhance uplink coverage, the NB-IoT system introduces retransmission mechanism in uplink physical channel. Due to the low-cost requirement, NB-IoT system is equipped with crystal oscillator NB-IoT terminal with a relatively low cost. Therefore, during long continuous uplink transmissions, the dissipation of terminal power amplifier causes temperature change of transmitter which leads to the crystal oscillator frequency deviation, which further seriously impacts uplink transmission performance of terminal and reduces data transmission efficiency. To correct this frequency variation, the uplink transmission interval

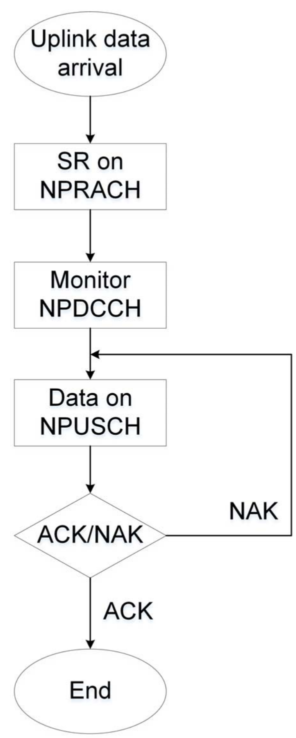


Fig. 7. NB-IoT uplink data transmission flow and related physical channel.

TABLE II
SIMULATION PARAMETERS

Element	Attribute		Value
EPS Bear Definitions	QoS Class Identifier		1 (GBR)
	Allocation Retention Priority		2
	Uplink Guaranteed Bit Rate		32 Kbps
	Dowlink Guaranteed Bit Rate		96 Kbps
	Uplink Maximum Bit Rate		32 Kbps
	Downlink Maximum Bit Rate		384 Kbps
Physical Layer Profiles	UL SC-FDMA Channel	Base Frequency	1920 MHz
		Bandwidth	0.2/3/5/10/15/20 MHz
		Cyclic Prefix Type	7 Symbols per Slot
	DL OFDMA Channel	Base Frequency	2110 MHz
		Bandwidth	0.2/3/5/10/15/20 MHz
		Cyclic Prefix Type	7 Symbols per Slot
eNodeB	Failure/Recovery Specification Time		200 seconds
UEs	Battery Capacity		5
	Maximum Transmission Power		10 mW
	Modulation and Coding Scheme Index		0/9/20/28
	Operating Power		100 mW

is introduced in NB-IoT in order to allow the terminal to suspend uplink transmission during long continuous transmission, switch to downlink during that period, and make synchronous tracking and frequency offset compensation by utilizing the NPSS/NSSS NRS signal. After a certain period of compensation (for instance, the frequency deviation is less than 50 Hz), the terminal will switch back to uplink and continue to transmit.

IV. NB-IOT SIMULATION

A. NB-IoT Network Architecture

Most target services scenes of NB-IoT are mini-packet transmissions, which generally do not support long-term and continuous channel quality change indication. Therefore, NB-IoT does not design a dynamic link adaption solution, but depends on selecting modulation and coding scheme (MCS) and retransmission times of data transmission according to the coverage level, thus the terminal is adjusted to different coverage levels to realize the semi-static link adaption. The MCS index is shown as Table I [51]. There are three common coverage levels including normal coverage, robust coverage, and extreme coverage, which correspond to three values of link losses (i.e., minimum coupling losses), 144 dB, 154 dB, and 164 dB, respectively.

The NB-IoT network architecture is mainly separated into five parts.

- NB-IoT terminal, which supports the accessing of IoT devices from various services, and allows them to access to the NB-IoT network by installing the corresponding SIM card.
- NB-IoT access network, i.e., the NB-IoT base station, mainly refers to the LTE base stations, i.e., evolved node B (eNodeB) which have already been built by operators. From the view point of the deployment mode, there are mainly three modes introduced in Section III.
- Core network, which enable connection between NB-IoT base station and NB-IoT cloud.
- NB-IoT cloud platform, wherein various processing can be completed, and results can be forwarded to the vertical industry center or NB-IoT terminals.
- Vertical industry center, which not only acquires NB-IoT business data from itself, but also completes the control of NB-IoT terminals.

The NB-IoT network architecture designed in this paper is shown in Fig. 5. In order to test the coverage range of NB-IoT network, we divided the whole network into four areas from long distance to short distance, namely by four MCSs: 1) MCS 0; 2) MCS 9; 3) MCS 20; and 4) MCS 28, which are shown in Table I. We use same modulation and coding strategy on each area, and take the MCS ID as the area ID. In each area, we deploy different numbers of NB-IoT terminals, namely user equipment (UE), which represent devices carried by different mobile users, and these devices are labeled by local ID in each area. All UE within the network communicate with NB-IoT base station, which is an improved LTE base station, i.e., eNodeB. The NB-IoT eNodeB model is presented in Fig. 6. As the access network part of NB-IoT, we build the model of all eNodeB processes from the bottom layer to the upper layer, including the S1 air interface which is connected with core network.

To complete the uplink data transmission, the UE needs to go through three steps: 1) NPRACH data transmission request; 2) NPDCCH feedback response; and 3) NPUSCH data transmission, as shown in Fig. 7. In this course, the MCS is sent down to the UEs through PDCCH, and the UEs

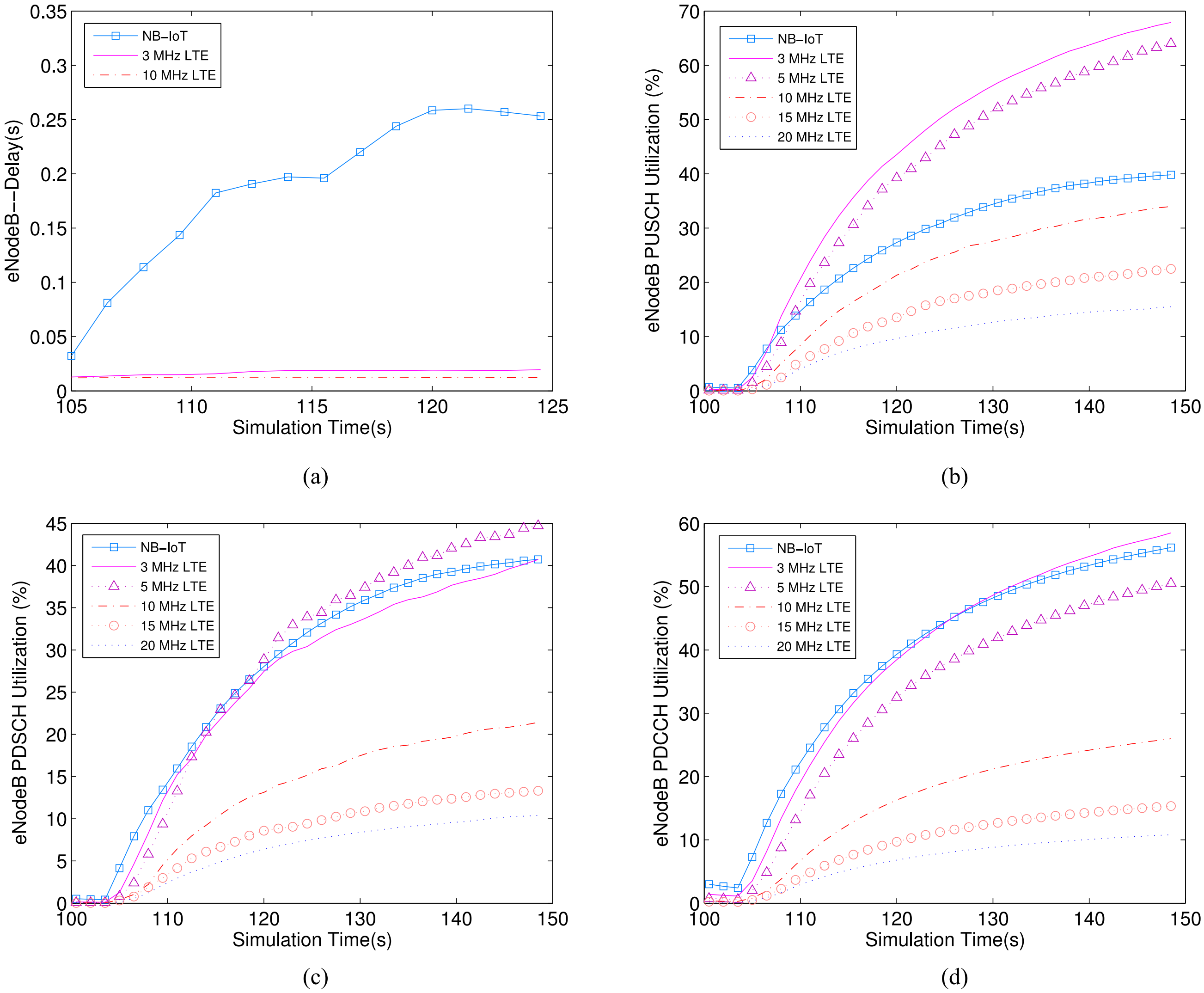


Fig. 8. Time delay and channel utilization of eNodeB. (a) Delay of eNodeB. (b) PUSCH utilization of eNodeB. (c) PDSCH utilization of eNodeB. (d) PDCCH utilization of eNodeB.

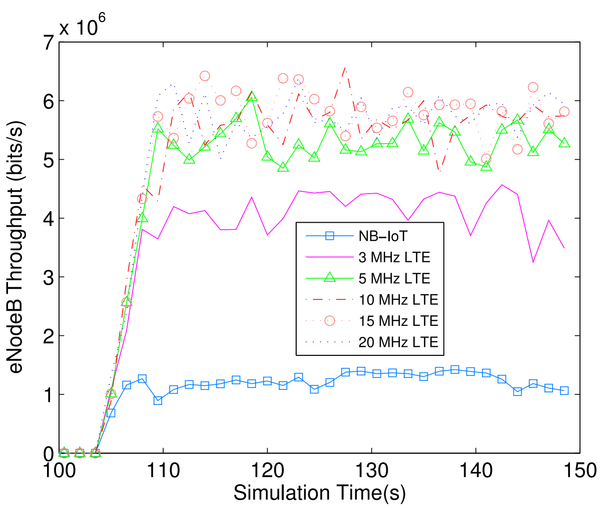


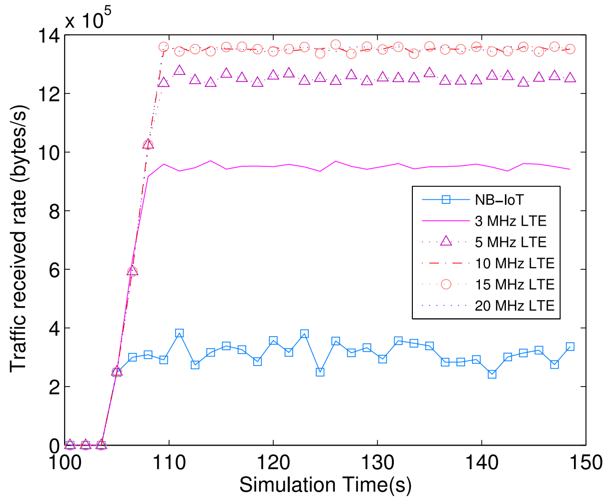
Fig. 9. Throughput of eNodeB.

make look-up table and obtain modulation model and transmission block size according to the MCS value, and then perform downlink demodulation or uplink modulation while the corresponding base stations connection with UEs makes the downlink modulation or uplink demodulation according to the MCS. Moreover, when and only when the NPRACH data transmission request is received successfully, and there are sufficient NPDCCH resources to respond to the data transmission request, as well as there are sufficient NPUSCH resources to carry such data business volume, the eNodeB responds to the uplink data transmission request from UE, and then unloads the data process or computation task to the NB-IoT Could plafrorm (IP Cloud) through the NB-IoT core network [evolved packet core (EPC)], or obtains data from server.

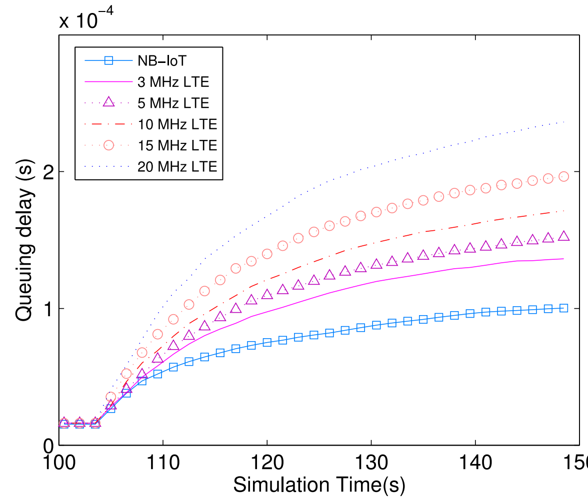
The values of important parameters considered in the simulations are presented in Table II. These values were selected to reflect real-world implementations of NB-IoT network based on prior research work. The simulations were run multiple times and presented results are averaged values.

B. Results and Analysis

We first compared time delay and channel utilization of NB-IoT network and LTE network with different channel



(a)



(b)

Fig. 10. Queuing delay from eNodeB to EPC. (a) Traffic received rate. (b) Queuing delay.

bandwidths. The obtained results are presented in Fig. 8. Since the channel bandwidth of NB-IoT was relatively narrow, the maximal data rate is 66.7 kb/s, while the LTE data rate reached 200 kb/s–100 Mb/s depending on channel bandwidth. Therefore, according to (1) in the case that the length of sent data frame is fixed, the sending time delay of NB-IoT is longer, as shown in Fig. 8(a). However, this delay result still meets the requirements defined by 3GPP that the uplink time delay shall not be longer than 10 s. When the sending cycle is fixed, according to (2), the channel utilization is directly proportional to the sending delay. Therefore, in comparison with LTE network with channel bandwidth of 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz, respectively, PUSCH utilization, PDSCH utilization, and PDCCH utilization of NB-IoT are higher, 40%, 42%, and 57%, respectively, as shown in Fig. 8(b)–(d)

$$\begin{aligned} T_{\text{total}} &= T_{\text{sent}} + T_{\text{tran}} + T_{\text{queue}} + T_{\text{proc}} \\ &= \frac{L_{\text{frame}}}{v_{\text{sent}}} + \frac{L_{\text{channel}}}{v_{\text{tran}}} + T_{\text{queue}} + T_{\text{proc}} \end{aligned} \tag{1}$$

$$\text{Utilization}_{\text{channel}} = \frac{L_{\text{frame}}}{v_{\text{sent}} C_{\text{sent}}}. \tag{2}$$

Thereinto, T_{sent} represents the sending time delay, L_{frame} represents the data frame length (b), v_{sent} represents the sending rate (b/s), T_{tran} represents the transmission time delay (s), L_{channel} represents the channel length (m), v_{tran} represents the transmission rate (m/s) of the electromagnetic wave on the channel, T_{total} represents the total time delay (s), T_{queue} represents the queuing time delay (s), T_{proc} represents the processing time delay (s), Utilization$_{\text{channel}}$ represents the channel utilization, and C_{sent} represents the sending cycle (s).

Fig. 9 shows the eNodeB throughput of NB-IoT, about 1 million bits/s, which is far less than the throughput of LTE network with channel bandwidth of 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. The results are presented in Fig. 9, respectively. This indirectly verifies that the data rate of NB-IoT is lower, which is more suitable for the low-bitrate services applications, such as intelligent metering, intelligent monitoring and, etc. Fig. 10 shows the queuing delay from eNodeB to EPC is presented in Fig. 10. The queuing delay is related to the eNodeB cache capacity, server speed, queue size, and the EPC group arrival rate. In this experiment, the eNodeB cache capacity, server speed, and queue size are fixed. The traffic received rate of NB-IoT network is lower, which is about 300 000 bytes/s, as shown in Fig. 10(a), which is only 25% of the LTE traffic network with bandwidth of 20 MHz. Therefore, the queuing delay of NB-IoT whith is about 0.0001 s, is lower than the that of LTE network with channel bandwidth of 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz, respectively, which has represents a significant improvement in comparison with the 0.00024 s of queuing delay of LTE network with a common bandwidth of 20 MHz, as shown in Fig. 10(b). In comparison with the sending delay and transmission delay, such a low queuing delay may be ignored in the calculation of total time delay.

The comparison of coverage range between NB-IoT network and LTE network with channel bandwidth of 20 MHz is presented in Fig. 11. This paper chooses one UE per area, namely UE_MCS_0_0, UE_MCS_9_0, UE_MCS_20_0, and UE_MCS_28_0, which are labeled from long distance to short distance and tested whether they receive the FTP traffic during the running process of NB-IoT and LTE network. Since channel bandwidth of NB-IoT is narrower than that of LTE network, the received traffic byte rate per second of NB-IoT is less than LTE network. As it is shown in Fig. 11(a) and (b), the UEs deployed in two long-distance areas can communicate with eNodeB only within the NB-IoT network. While in two areas relatively near to the eNodeB, both in NB-IoT network and LTE network, the UEs can communicate with the eNodeB in real time, as shown in Fig. 11(c) and (d). Since NB-IoT introduces the retransmission mechanism in downlink physical channel, and improves demodulation threshold through the diversity gain and merging gain of retransmission, the network can enhances downlink coverage. To solve the resource blocking problem of enhanced coverage, the periodic downlink transmission interval is introduced. As it was

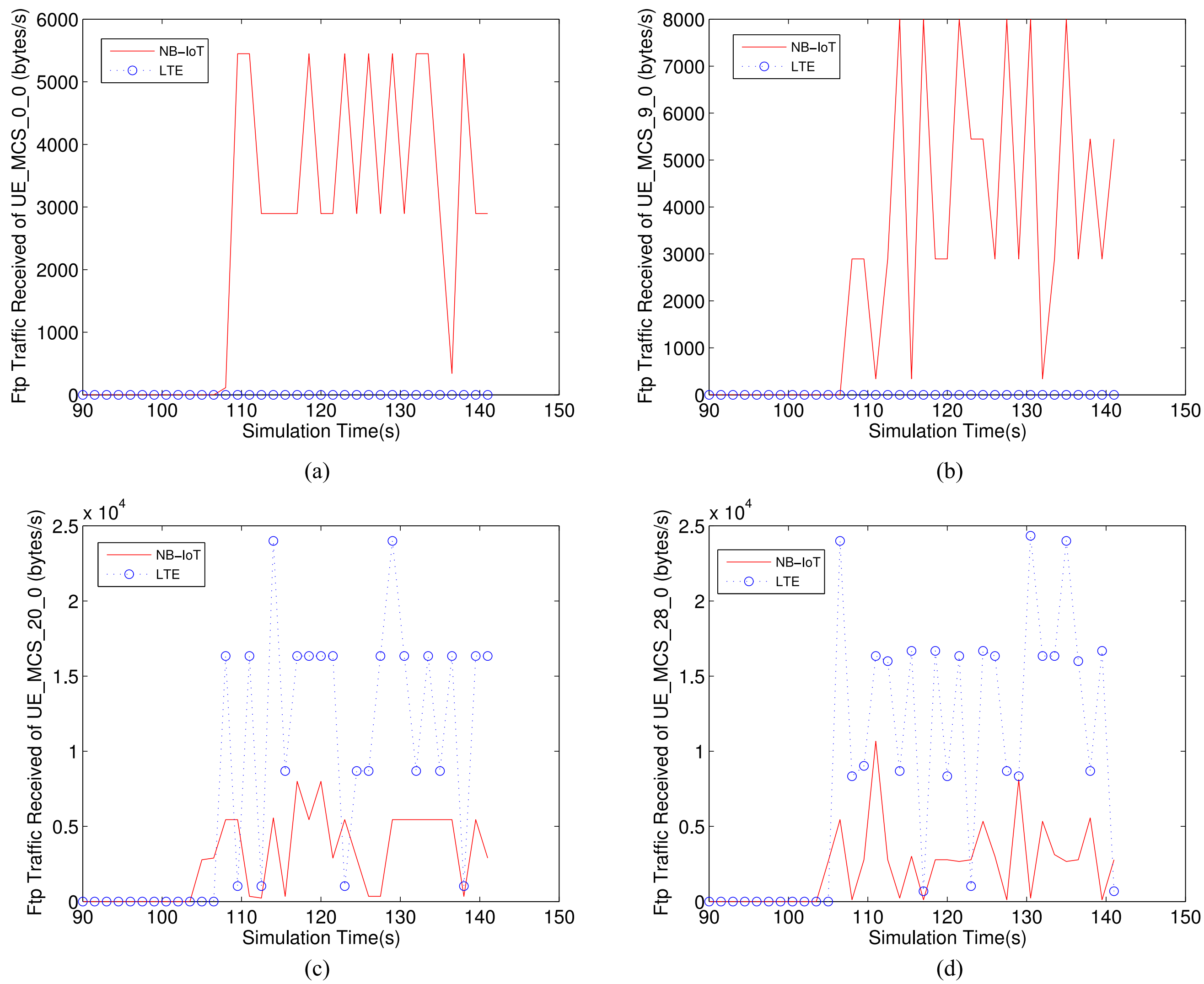


Fig. 11. Coverage range contrast between NB-IoT network and LTE network with 20 MHz bandwidth. (a) FTP traffic received of UE_MCS_0_0. (b) FTP traffic received of UE_MCS_9_0. (c) FTP traffic received of UE_MCS_20_0. (d) FTP traffic received of UE_MCS_28_0.

previously mentioned, for the requirement of maximal 20 dB coverage improvement, in the in-band deployment mode, the NPDCCH needs about 200–350 ms of retransmission while NPDSCH needs about 1200–1900 ms of retransmission, and if the resources are continuously occupied by NPDCCH and NPDSCH, the uplink/downlink authorization or downlink business transmission of other terminals will be blocked. Therefore, the FTP traffic received by UEs presents a periodic variation.

V. Conclusion

This paper introduces a development of NB-IoT technology and its main characteristics and design objectives according to 3GPP R13. In addition, the related literature about NB-IoT modeling and algorithm analysis is presented. Then we explain current problems of NB-IoT system-level modeling based on visualized simulation platform. Nevertheless, this paper constructs an NB-IoT model based on OPNET, and verifies its characteristics, such as wide coverage, high channel utilization, and etc.

In this paper, we focused on model design and realization aiming at physical layer characteristics of NB-IoT. We analyzed correlated uplink and downlink characteristics of NB-IoT, and designed and constructed the NB-IoT model based on LTE network. Lastly, we used the constructed NB-IoT model to perform simulations, and we compared NB-IoT network with LTE network under channel bandwidth of 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. The simulation results have verified the NB-IoT performance defined by 3GPP, that NB-IoT uplink time delay is lower than 10 s, channel utilization is higher than in LTE network, and coverage area is larger than in LTE network.

The discussions and modeling presented in this paper aim to provide a comprehensive overview and big-picture of exciting solutions on this subject. In our future work, we will continue to design and improve the NB-IoT model based on OPNET. Nevertheless, we will further improve and optimize air interface layer, access network and core network of NB-IoT based on LTE network, in order to reach the expected requirements.

ACKNOWLEDGMENT

The authors would like to extend their sincere appreciation to the Deanship of Scientific Research at King Saud University, Riyadh, Saudi Arabia, for funding this research group.

REFERENCES

[1] J. Wan *et al.*, "Software-defined industrial Internet of Things in the context of industry 4.0," *IEEE Sensors J.*, vol. 16, no. 20, pp. 7373–7380, Oct. 2016.
[2] W. Dai, M. Qiu, L. Qiu, L, Chen, and A. Wu, "Who moved my data? Privacy protection in smartphones," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 20–25, Jan. 2017.
[3] M. Qiu and E. H.-M. Sha, "Cost minimization while satisfying hard/soft timing constraints for heterogeneous embedded systems," *ACM Trans. Design Autom. Electron. Syst.*, vol. 14, no. 2, pp. 1–30, Apr. 2009.
[4] M. Qiu, Z. Ming, J. Li, K. Gai, and Z. Zong, "Phase-change memory optimization for green cloud with genetic algorithm," *IEEE Trans. Comput.*, vol. 64, no. 12, pp. 3528–3540, Dec. 2015.
[5] K. Lin, M. Chen, J. Deng, M. M. Hassan, and G. Fortino, "Enhanced fingerprinting and trajectory prediction for IoT localization in smart buildings," *IEEE Trans. Autom. Sci. Eng.*, vol. 13, no. 3, pp. 1294–1307, Jul. 2016.
[6] X. Hou *et al.*, "Vehicular fog computing: A viewpoint of vehicles as the infrastructures," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3860–3873, Jun. 2016.
[7] X. Xiong, K. Zheng, R. Xu, W. Xiang, and P. Chatzimisios, "Low power wide area machine-to-machine networks: Key techniques and prototype," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 64–71, Sep. 2015.
[8] Y. Li and M. Chen, "Software-defined network function virtualization: A survey," *IEEE Access*, vol. 3, pp. 2542–2553, 2015.
[9] "Cellular system support for ultra-low complexity and low throughput Internet of Things," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 45.820, 2015.
[10] *E-UTRA Physical Channels and Modulation-Chap.10 Narrowband IoT*, 3GPP Standard TS 36.211, 2016.
[11] *Standardization of NB-IoT Completed*, 3GPP, Sophia Antipolis, France, 2016. [Online]. Available: http://www.3gpp.org/news-events/3gpp-news/1785-nb_iot_complete
[12] A. Rico-Alvarino *et al.*, "An overview of 3GPP enhancements on machine to machine communications," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 14–21, Jun. 2016.
[13] C. Hoymann *et al.*, "LTE release 14 outlook," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 44–49, Jun. 2016.
[14] F. Liu, K. Zheng, W. Xiang, and H. Zhao, "Design and performance analysis of an energy-efficient uplink carrier aggregation scheme," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 2, pp. 197–207, Feb. 2014.
[15] K. Lin, W. Wang, X. Wang, W. Ji, and J. Wan, "QoE-driven spectrum assignment for 5G wireless networks using SDR," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 48–55, Dec. 2015.
[16] H. Wu, "Recent advances in technology and application of Internet of Things," in *Proc. Internet Things Conf.*, Shanghai, China, 2017, p. 1.
[17] G.-H. Dai and J.-H. Yu, "Research on NB-IoT background, standard development, characteristics and the service," *Mobile Commun.*, vol. 40, no. 7, pp. 31–36, 2016.
[18] K. Lin, W. Wang, Y. Bi, M. Qiu, and M. M. Hassan, "Human localization based on inertial sensors and fingerprints in the industrial Internet of Things," *Comput. Netw.*, vol. 101, pp. 113–126, Jun. 2016.
[19] M. Chen, P. Zhou, and G. Fortino, "Emotion communication system," *IEEE Access*, vol. 5, pp. 326–337, 2017.
[20] M. Chen *et al.*, "Smart home 2.0: Innovative smart home system powered by botanical IoT and emotion detection," *Mobile Netw. Appl.*, vol. 6, pp. 1–11, 2017.
[21] X. Qian and M. Mu, "NB-IoT standardization, technical characteristics and industrial development," *Inf. Res.*, pp. 23–216, May 2016.
[22] F. Xu *et al.*, "Trajectory recovery from ash: User privacy is NOT preserved in aggregated mobility data," in *Proc. 26th Int. Conf. World Wide Web*, 2017, pp. 1241–1250.
[23] M. Chen, Y. Hao, K. Hwang, L. Wang, and L. Wang, "Disease prediction by machine learning over big data from healthcare communities," *IEEE Access*, vol. 5, pp. 8869–8879, 2017.
[24] W. Liu, J. Dong, and N. Liu, "NB-IoT key technology and design simulation method," *Telecommun. Sci.*, pp. 144–148, Jul. 2016.
[25] A. Laya, A. Luis, and A. Jesus, "Is the random access channel of LTE and LTE-A suitable for M2M communications? A survey of alternatives," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 4–16, 1st Quart., 2014.
[26] Y. Zhang, M. Qiu, C.-W. Tsai, M. M. Hassan, and A. Alamri, "Health-CPS: Healthcare cyber-physical system assisted by cloud and big data," *IEEE Syst. J.*, vol. 11, no. 1, pp. 88–95, Mar. 2017.
[27] M. Chen, J. Yang, Y. Hao, S. Mao, and K. Hwang, "A 5G cognitive system for healthcare," *Big Data Cogn. Comput.*, vol. 1, no. 1, p. 1, 2017, doi: 10.3390/bdcc1010002.
[28] M. Chen *et al.*, "Wearable 2.0: Enabling human-cloud integration in next generation healthcare systems," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 54–61, Jan. 2017.
[29] Q. Liu, Y. Ma, M. Alhussein, Y. Zhang, and L. Peng, "Green data center with IoT sensing and cloud-assisted smart temperature control system," *Comput. Netw.*, vol. 101, pp. 104–112, Jun. 2016.
[30] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe, and A. Ghosh, "NB-IoT system for M2M communication," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Doha, Qatar, 2016, pp. 428–432.
[31] M. Chen, J. Wan, S. Gonzalez, X. Liao, and V. C. M. Leung, "A survey of recent developments in home M2M networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 98–114, 1st Quart., 2014.
[32] K. Zheng, F. Liu, L. Lei, C. Lin, and Y. Jiang, "Stochastic performance analysis of a wireless finite-state Markov channel," *IEEE Trans. Wireless Commun.*, vol. 62, no. 4, pp. 1450–1458, Feb. 2013.
[33] N. Mangalvedhe, R. Ratasuk, and A. Ghosh, "NB-IoT deployment study for low power wide area cellular IoT," in *Proc. IEEE 27th IEEE Annu. Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Valencia, Spain, 2016, pp. 1–6.
[34] A. Adhikary, X. Lin, and Y.-P. E. Wang, "Performance evaluation of NB-IoT coverage," in *Proc. IEEE 84th IEEE Veh. Technol. Conf. (VTC Fall)*, Montreal, QC, Canada, 2016, pp. 1–5.
[35] M. Lauridsen, I. Z. Kovacs, P. Mogensen, M. Sorensen, and S. Holst, "Coverage and capacity analysis of LTE-M and NB-IoT in a rural area," in *Proc. IEEE 84th IEEE Veh. Technol. Conf. (VTC Fall)*, Montreal, QC, Canada, 2016, pp. 1–5.
[36] X. Lin, A. Adhikary, and Y.-P. E. Wang, "Random access preamble design and detection for 3GPP narrowband IoT systems," *IEEE Wireless Commun. Lett.*, vol. 5, no. 6, pp. 640–643, Dec. 2016.
[37] A. Ali and W. Hamouda, "On the cell search and initial synchronization for NB-IoT LTE systems," *IEEE Commun. Lett.*, vol. 21, no. 8, pp. 1843–1846, Aug. 2017.
[38] H. Kroll, M. Korb, B. Weber, S. Willi, and Q. Huang, "Maximum-likelihood detection for energy-efficient timing acquisition in NB-IoT," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, San Francisco, CA, USA, 2017, pp. 1–5.
[39] G. Fortino, R. Gravina, W. Russo, and C. Savaglio, "Modeling and simulation of Internet of Things systems: A hybrid agent-oriented approach," *IEEE Comput. Sci. Eng.*, to be published, doi: 10.1109/MCSE.2017.59.
[40] G. Fortino, "Agents meet the IoT: Toward ecosystems of networked smart objects," *IEEE Syst. Man Cybern. Mag.*, vol. 2, no. 2, pp. 43–47, Apr. 2016, doi: 10.1109/MSMC.2016.2557483.
[41] G. O. Fortino, A. Guerrieri, W. Russo, and C. Savaglio, "Towards a development methodology for smart object-oriented IoT systems: A metamodel approach," in *Proc. IEEE Comput. Sci. Eng.*, Kowloon, China, 2015, pp. 1297–1302.
[42] C. H. Liu, J. Fan, J. W. Branch, and K. K. Leung, "Toward QoI and energy-efficiency in Internet-of-Things sensory environments," *IEEE Trans. Emerg. Topics Comput.*, vol. 2, no. 4, pp. 473–487, Dec. 2014.
[43] C. H. Liu, J. Fan, P. Hui, J. Wu, and K. K. Leung, "Toward QoI and energy efficiency in participatory crowdsourcing," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4684–4700, Oct. 2015.
[44] M. Koseoglu, "Lower bounds on the LTE-A average random access delay under massive M2M arrivals," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 2104–2115, May 2016.
[45] B. Yang, G. Zhu, W. Wu, and Y. Gao, "M2M access performance in LTE-A system," *Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 1, pp. 3–10, 2014.
[46] X. Wang, Z. Sheng, S. Yang, and V. C. M. Leung, "Tag-assisted social-aware opportunistic device-to-device sharing for traffic offloading in mobile social networks," *IEEE Wireless Commun. Mag.*, vol. 23, no. 4, pp. 60–67, Aug. 2016.
[47] G. C. Madueño, Č. Stefanović, and P. Popovski, "Reengineering GSM/GPRS towards a dedicated network for massive smart metering," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, Venice, Italy, 2014, pp. 338–343.

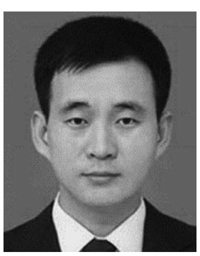
[48] H. Wang *et al.*, "A measurement study of device-to-device sharing in mobile social networks based on spark," *Wiley Concurrency Comput. Pract. Exp.*, vol. 29, no. 16, p. 1, 2017.
[49] M. Chen *et al.*, "Mobility-aware caching and computation offloading in 5G ultra-dense cellular networks," *Sensors*, vol. 16, no. 7, pp. 974–987, 2016.
[50] C. Marco and V. Lorenzo, "A study on M2M traffic and its impact on cellular networks," in *Proc. IEEE 2nd World Forum Internet Things*, Milan, Italy, 2015, pp. 154–159.
[51] B. Lu, "Discussion on Internet of Things coverage enhancement technology of NB-IoT," *Mobile Commun.*, vol. 40, no. 19, pp. 55–59, 2016.

Yiming Miao received the B.Sc. degree from the College of Computer Science and Technology, Qinghai University, Xining, China, in 2016. She is currently pursuing the Ph.D. degree at the School of Computer Science and Technology, Huazhong University of Science and Technology, Wuhan, China.

She has authored two papers. Her current research interests include IoT sensing, healthcare big data, and emotion-aware computing.

Wei Li received the graduated degree from the Wuhan University of Technology (WHUT), Wuhan, China, in 2015. She is currently pursuing the doctor's degree at the Embedded and Pervasive Computing Laboratory, Huazhong University of Science and Technology (HUST), Wuhan.

She was with WHUT. She actively participated in all kinds of activities and read lots of books on computer programming. She was recommended to HUST without taking part in the entrance examination. Her current research interests include pervasive computing, Internet of Things, and mobile cloud computing.



Daxin Tian (M'13–SM'16) received the B.S., M.S., and Ph.D. degrees in computer science from Jilin University, Changchun, China, in 2002, 2005, and 2007, respectively.

He is an Associate Professor with the School of Transportation Science and Engineering, Beihang University, Beijing, China. His current research interests include mobile computing, intelligent transportation systems, vehicular ad hoc networks, and swarm intelligence.

M. Shamim Hossain (SM'09) received the Ph.D. degree in electrical and computer engineering from the University of Ottawa, Ottawa, ON, Canada.

He is an Associate Professor with King Saud University, Riyadh, Saudi Arabia. He has authored or co-authored around 120 publications including refereed IEEE/ACM/Springer/Elsevier journals, conference papers, books, and book chapters. His current research interests include serious games, social media, IoT, cloud and multimedia for healthcare, smart health, and resource provisioning for big data processing on media clouds.

Dr. Hossain was a recipient of a number of awards including the Best Conference Paper Award, the 2016 *ACM Transactions on Multimedia Computing, Communications and Applications*, Nicolas D. Georganas Best Paper Award, and the Research in Excellence Award from King Saud University. He is on the Editorial Board of IEEE ACCESS, *Computers and Electrical Engineering* (Elsevier), *Games for Health Journal*, and the *International Journal of Multimedia Tools and Applications* (Springer). He served as a Guest Editor for the IEEE TRANSACTIONS ON INFORMATION TECHNOLOGY IN BIOMEDICINE (currently the IEEE JOURNAL OF BIOMEDICAL AND HEALTH INFORMATICS), the *International Journal of Multimedia Tools and Applications* (Springer), *Cluster Computing* (Springer), *Future Generation Computer Systems* (Elsevier), *Computers and Electrical Engineering* (Elsevier), and the *International Journal of Distributed Sensor Networks*. He currently serves as a Lead Guest Editor of *IEEE Communication Magazine*, the IEEE TRANSACTIONS ON CLOUD COMPUTING, IEEE ACCESS, and *Sensors* (MDPI). He has served as the Co-Chair, General Chair, Workshop Chair, Publication Chair, and Technical Program Chair for over 12 IEEE and ACM conferences and workshops. He is a member of the ACM and ACM SIGMM.

Mohammed F. Alhamid (GS'08–M'10) received the master's and Ph.D. degrees from the School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada.

He served over seven years as a Research Assistant with the Multimedia Research Laboratory, University of Ottawa/Université d'Ottawa. He is also a Research Member with the Discover Laboratory. His current research interests include recommender systems, social media mining, big data, ambient intelligent environment, and software engineering.