IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 22, 2016, accepted January 25, 2017, date of publication February 6, 2017, date of current version March 13, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2664418

Uplink Scheduling and Link Adaptation for Narrowband Internet of Things Systems

CHANGSHENG YU[1,2], (Member, IEEE), LI YU[1], YUAN WU[1], YANFEI HE[1], AND QUN LU[1]
[1]College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China
[2]Nokia Solutions and Networks System Technology, Co., Ltd., Hangzhou 310000, China

Corresponding author: C. Yu (flyycs@zju.edu.cn)

ABSTRACT Narrowband Internet of Things (NB-IoT) is a new narrow-band radio technology introduced in the Third Generation Partnership Project release 13 to the 5th generation evolution for providing low-power wide-area IoT. In NB-IoT systems, repeating transmission data or control signals has been considered as a promising approach for enhancing coverage. Considering the new feature of repetition, link adaptation for NB-IoT systems needs to be performed in 2-D, i.e., the modulation and coding scheme (MCS) and the repetition number. Therefore, existing link adaptation schemes without consideration of the repetition number are no longer applicable. In this paper, a novel uplink link adaptation scheme with the repetition number determination is proposed, which is composed of the inner loop link adaptation and the outer loop link adaptation, to guarantee transmission reliability and improve throughput of NB-IoT systems. In particular, the inner loop link adaptation is designed to cope with block error ratio variation by periodically adjusting the repetition number. The outer loop link adaptation coordinates the MCS level selection and the repetition number determination. Besides, key technologies of uplink scheduling, such as power control and transmission gap, are analyzed, and a simple single-tone scheduling scheme is proposed. Link-level simulations are performed to validate the performance of the proposed uplink link adaptation scheme. The results show that our proposed uplink link adaptation scheme for NB-IoT systems outperforms the repetition-dominated method and the straightforward method, particularly for good channel conditions and larger packet sizes. Specifically, it can save more than 14% of the active time and resource consumption compared with the repetition-dominated method and save more than 46% of the active time and resource consumption compared with the straightforward method.

INDEX TERMS Narrowband Internet of Things (NB-IoT), coverage enhancement, low complexity, link adaptation.

I. INTRODUCTION

The Internet of Things (IoT) is a promising paradigm that is rapidly gaining ground in future wireless communications. The basic concept of IoT is the pervasive presence of a variety of things or objects around us, such as radio-frequency identification (RFID) tags, sensors, actuators, mobile phones, and so forth. These things or objects are able to interact with each other and cooperate with their neighbors to achieve common goals through unique addressing schemes. However, the rapid growth of wireless communications and mobile internet services makes it necessary to improve the performance of current IoT technology to achieve requirements such as low cost, low complexity, coverage enhancement and so forth [1]–[5]. Techniques regarding IoT were well studied in current literatures. Specifically, in [4], the authors presented a systematical review about IoT which includes different definitions, key technologies, open issues and major challenges of it. Furthermore, in [5], the authors provided a systematical survey regarding IoT in industry for the first time. It reviewed extensive researches, key enabling technologies, major IoT applications of IoT in industry, and identified research trends and challenges. Fig. 1 presents a comparison of different technologies for IoT and the evolution towards to 5G. Among these technologies, Narrowband Internet of Things (NB-IoT) is a novel narrowband radio technology specifically designed for IoT, which can be directly deployed in Global System for Mobile Communications (GSM) or Long-Term Evolution (LTE) networks for reducing deployment costs [6]. At a recent plenary meeting in South Korea, the Third Generation Partnership Project (3GPP) completed the standardization of NB-IoT [7], in which NB-IoT is regarded to be a very important technology and a large step for 5G IoT evolution. Industries, including Ericsson, Nokia, and Huawei, have shown great interests in NB-IoT as part of

5G systems, and spent lots of effort in the standardization of NB-IoT [8], which has been widely considered as a main technique for next-generation wireless communications. NB-IoT is expected to provide improved coverage, and support a massive number of low-throughput devices, low delay sensitivity, ultra-low device costs, and low device power consumption [9]. How to achieve these benefits, particularly improved coverage, bring great challenges. In 3GPP standardization, repeating transmission data and the associated control signaling several times has been utilized as a base solution to achieve coverage enhancement for NB-IoT.

Taking into account the new feature of repetition, link adaptation for NB-IoT systems need to be performed in two dimensions, i.e., the *modulation and coding scheme (MCS) level selection* as in traditional LTE systems, and the *repetition number determination*. The reasons are as follows. First, different MCS levels influence throughput of system directly, low MCS and high power will improve transmit reliability and enhance coverage, but reduce system throughput; Second, according to 3GPP Release 13, repeating transmission data or control signals has been selected as a promising approach to enhance coverage of NB-IoT systems, since more repetition number will enhance the transmission reliability, but cause spectral efficiency loss. Thus, link adaptation scheme needs to get trade-off between transmit reliability and throughput of system by selecting suitable MCS and repetition. Therefore, the existing link adaptation schemes without consideration of repetition number are no longer applicable. It is crucial to design an appropriate link adaptation scheme integrated with a proper selection of repetition number and MCS for NB-IoT systems, which is the objective of this paper. In this paper, we focus on analyzing key technologies in uplink scheduling and designing an *uplink* link adaptation scheme for NB-IoT systems. The reason is that uplink transmission for NB-IoT systems is considerably more complicated than downlink transmission, which will be explained later. Furthermore, since the channel condition of NB-IoT systems is much more complicated,[1] which leads to rapid changes of the transmission Block Error Ratio (BLER), we introduce an inner loop link adaptation procedure that focuses on adjusting the repetition number based on periodically measured transmission BLER. The purpose of the inner loop link adaptation is to guarantee the transmission BLER to the target. Accordingly, we refer to the former as outer loop link adaptation, i.e., MCS level selection and repetition number determination.

The contributions of this paper can be summarized as follows:

- We provide a brief survey of NB-IoT, including protocol volume, key technologies of uplink scheduling, applications, and several open issues.
- We propose an uplink link adaptation scheme for NB-IoT systems. The proposed scheme is composed of the inner loop link adaptation and the outer loop link adaptation. The purpose of the inner loop link adaptation is to guarantee transmission BLER by adjusting the repetition number, and the outer loop link adaptation is to select the MCS level and repetition number based on ACK/NACKs.
- Extensive simulation results are provided to evaluate the performance of the proposed uplink link adaptation scheme. The results show that our proposed scheme outperforms the repetition-dominated and straightforward methods.[2]

A. LITERATURE REVIEW OF LINK ADAPTATION

Link adaptation has been widely studied in different types of wireless communication systems. Link adaptation was first proposed in [10], in which an analytical outer loop power control model was studied to handle the Signal-to-Interference Ratio (SIR) fluctuation. Li *et al.* [11] investigated the impact of uplink interference on the efficiency of link adaptation in heterogeneous networks, and they further proposed a cooperative uplink link adaptation scheme by exploiting the cooperation among base stations. Durn *et al.* [12] designed a novel self-optimization algorithm for improving the convergence speed of the outer loop link adaptation (OLLA) in the downlink of LTE systems. Xia *et al.* [13] proposed the Auto-Rate Fallback for High-Throughput (ARFHT) algorithm for the emerging high-throughput IEEE 802.11n wireless networks. ARFHT extends the legacy link adaptation algorithms for Single-Input-Single-Output (SISO) wireless networks to Multiple-Input-Multiple-Output (MIMO)-based 802.11n wireless networks. Cavalcante *et al.* [14] provided a system-level analysis of OLLA for IEEE 802.16e systems. Sarret *et al.* [15] proposed a dynamic OLLA (d-OLLA) algorithm to address the large Signal-to-Interference plus Noise Ratio (SINR) fluctuation for 5G of wireless communication systems. Blanquez-Casado *et al.* [16] provided a thorough analysis of OLLA, including its dynamics and convergence conditions. Based on the analysis, they proposed an enhanced OLLA (eOLLA) scheme to adaptively modify the step size and to update the offset according to the reception conditions.

Moreover, note that Mu *et al.* [17] investigated the downlink link adaptation scheme that coordinates the MCS selection and the repetition number determination with the consideration of low-complexity feature for LTE-based Machine-Type Communication (MTC) systems. This is the first time that repetition was taken into account in link adaptation in wireless communication systems. However, it is quite different from our work in this paper. First, we aim at

[1] NB-IoT is new technology designed for Internet of Things whose applications are very diverse, including smart cities, smart environment, smart water, smart metering, security and emergencies, retail, logistics, industrial control, smart agriculture, smart animal farming, domestic and home automation, eHealth and so on. Thus the channel condition is very complicated according to different application scenarios.

[2] In the repetition-dominated method, based on the feedback ACK/NACKs, we first adjust the repetition number and then update the MCS level. In the straightforward method, we always set the MCS level as 0 and use the maximum resource unit to transmit the packet, and we adjust the repetition number only.

	WIFI	BLE	ZIGBEE Pro	SIGFOX	LoRa	LTE-M/(eMTC) (Rel. 13)	EC-GSM (Rel. 13)	NB-IoT (Rel. 13)	5G (targets)
Coverage Area	17–30+ (meters)	1–10+ (meters)	1–100+ (meters)	<12km 160 dB	< 10km 157 dB	< 10km 156 dB	< 15km 164 dB	<15km 164 dB	<12km 160 dB
Spectrum Bandwidth	2.4G 802.11	2.4G 802.15.1	2.4G 802.15.4	Unlicensed 900MHz 100Hz	Unlicensed 900MHz <500kHz	Licensed 7-900MHz 1.4 MHz shared	Licensed 8-900MHz shared	Licensed 7-900MHz 200 kHz shared	Licensed 7-900MHz shared
Rate	150Mbps+	1Mbps	250kbps	<100bps	<10 kbps	< 1 Mbps	10kbps	<50 kbps	< 1 Mbps
Terminal Cost	4.00$ (2016)	4.00$ (2016)	3.00$ (2016)	4.00$ (2015) 2.64$ (2020)	4.00$ (2015) 2.64$ (2020)	5.00$ (2015) 3.30$ (2020)	4.5$ (2015) 2.97$ (2020)	4$ (2015) 2-3$ (2020)	<$2
Network Reforming	None	None	None	Large	Large	Small	Moderate (LTE reuse)	Small to Moderate	Requires 5G NWs

FIGURE 1. Comparison of IoT technologies.

designing an uplink link adaptation scheme for 200KHz bandwidth NB-IoT systems, which is very different from downlink link adaptation for 1.4MHz bandwidth MTC systems. NB-IoT systems are defined with much narrower bandwidth and bigger repetition number than MTC systems, which thus can get considerable gains in coverage enhancement in comparison with that without repetition. Therefore, without repetition determination in NB-IoT systems violates the 3GPP purpose. Moreover, the proposed downlink link adaptation scheme in [17] is *static* for MCS level selection and repetition number determination. However, our work in this paper focus on dynamically choosing the MCS level and repetition number based on the real-time channel conditions. To the best of our knowledge, the uplink link adaptation specific to NB-IoT systems has not been previously studied, which is the objective of this paper.

The remainder of this paper is organized as follows. In Section II, we provide a brief survey of NB-IoT. We investigate the uplink link adaptation scheme for NB-IoT systems in Section III. Section IV provides the simulation results, and Section V concludes this paper.

II. BRIEF SURVEY OF NB-IoT AND PROBLEM STATEMENT

This section focuses on providing a brief survey of NB-IoT, including protocol volume, key technologies, applications, and several open issues. Then, we briefly introduce link adaptation technology and state the problem explored in this paper.

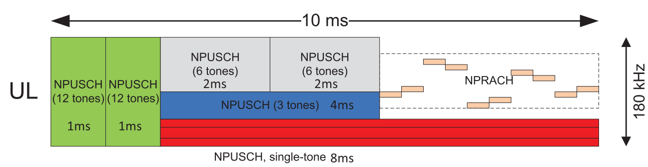

FIGURE 2. Uplink transmission for NB-IoT systems. NPUSCH represents narrowband physical uplink shared channel, and NPRACH represents narrowband physical random access channel.

A. PROTOCOL VOLUME OF NB-IoT

1) DOWNLINK AND UPLINK TRANSMISSIONS

NB-IoT systems require at least 180 kHz bandwidth for both downlink and uplink transmissions. The downlink transmission is based on conventional Orthogonal Frequency Division Multiple Access (OFDMA) in LTE with 15 kHz subcarrier spacing. The slot, subframe, and frame durations are 0.5 ms, 1 ms, and 10 ms [20], respectively. In essence, an NB-IoT carrier uses one LTE Physical Resource Block (PRB) in the frequency domain, which corresponds to 12 subcarries with each of 15kHZ. For the uplink transmission, both single-tone and multi-tone[3] transmissions (i.e., 3, 6, and 12 tones) are supported, as shown in Fig. 2. Single-tone transmission supports two numerologies: 15 kHz and 3.75 kHz. In 3GPP [20], one Resource Unit (RU) is a schedulable unit in Narrowband Physical Uplink Shared Channel (NPUSCH) transmission for the data, which consists of 15 kHz: 1 ms for

[3] Tone means sub-carrier here.

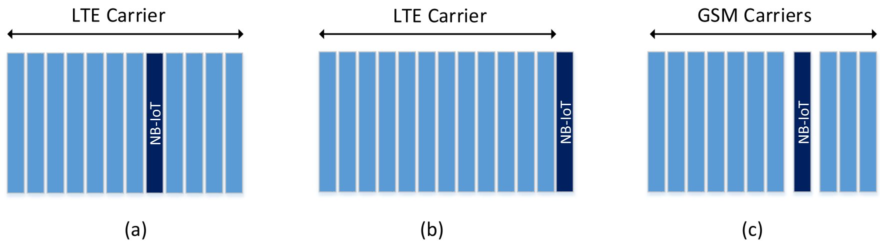

FIGURE 3. **Illustration of three different deployment operations for NB-IoT. (a) In-Band. (b) Guard-Band. (c) Stand-Alone.**

12 tones, 2 ms for 6 tones, 4 ms for 3 tones, 8 ms for a single tone, or 32 ms for a single tone of 3.75 kHz. The 15 kHz numerology is identical to LTE and thus achieves the best coexistence performance with LTE in the uplink. Multi-tone transmission is based on Single Carrier Frequency Division Multiple Access (SCFDMA) with the same 15 kHz subcarrier spacing, 0.5 ms slot, and 1 ms subframe as LTE. According to the NB-IoT standard [19], both single-tone and multi-tone are mandatory for the terminal, but User Equipment (UE) may indicate a lack of network interoperability testing for multi-tone mode in first implementation phase of NB-IoT systems and single-tone mode is always supported [19].

2) DEPLOYMENT OPTIONS

NB-IoT can be directly deployed in the GSM or LTE spectrum to reduce deployment costs. In particular, it is designed to support three different modes of operation:

- **In-Band Operation:** In this operation, NB-IoT is deployed inside an LTE carrier, as shown in Fig. 3(a). The narrowband consists of one resource block with 180 kHz. LTE and NB-IoT share transmit power at the eNB.
- **Guard-Band Operation:** In this operation, the NB-IoT channel is placed in a guard band of an LTE channel, as shown in Fig. 3(b). The NB-IoT downlink can share the same power amplifier as the LTE channel.
- **Stand-Alone Operation:** In this operation, NB-IoT is deployed as a standalone with at least 180 kHz of the GSM spectrum, as shown in Fig. 3(c). All the transmit power at the base station can be used for NB-IoT, which thus significantly enhances the coverage.

The deployment operations, namely, in-band, guard-band, and stand-alone, should be transparent to a UE when it is first turned on and searches for an NB-IoT carrier. Similar to existing LTE UEs, the channel raster is 100 kHz in all three operations.

3) REPETITION

Repetition is the key solution adopted by NB-IoT to achieve enhanced coverage with low complexity. Additionally, for one complete transmission, repetition of the transmission should be applied to both data transmission and the associated control signaling transmission. In NB-IoT systems, before each NPUSCH transmission, related control information,

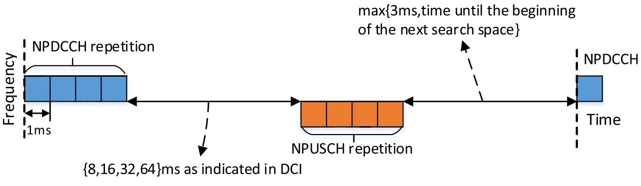

FIGURE 4. **Illustration of repetition during one transmission. DCI means downlink control information.**

including RU number, selected MCS and repetition, should first be transmitted through a Narrowband Physical Downlink Control Channel (NPDCCH). In particular, repetition for NB-IoT can only be selected among {1, 2, 4, 8, 16, 32, 64, 128}, the number means the repetition number of the same transmission block. Fig. 4 presents an illustration of repetition in NB-IoT, where both NPDCCH and NPUSCH transmission block with same content are repeated four times during one transmission.

B. KEY TECHNOLOGIES AND APPLICATIONS

1) UPLINK SCHEDULING TECHNOLOGIES

Uplink scheduling technologies primarily include NPRACH and NPUSCH scheduling. Lin *et al.* [18] studied NPRACH design and detection. Wang *et al.* [9] investigated several important technologies in NPUSCH uplink scheduling, such as timing and HARQ, but they did not mention how power control and uplink transmission gap will work. We propose a simple single-tone scheduling scheme, in which eleven tones can be scheduled for data transmission with NPUSCH format 1 and another single tone can be scheduled as ACK/NACK feedback for downlink transmission with NPUSCH format 2, different UE schedule different tone from frequency dimension, and schedule different resource unit from time dimension. To achieve better uplink throughput performance and avoid radio link failure, uplink power control and transmission gap shall be considered.

a: UPLINK OPEN LOOP POWER CONTROL

NB-IoT only supports open loop power control in uplink according to [21] chapter 16, definition for low complexity. Open loop means UE can determine uplink transmission power according to MCS and RU, eNB can not send power control command to UE for its uplink transmission power. The UE transmit power $P_{\mathrm{NPUSCH,c}}(i)$ for NPUSCH transmission in NB-IoT uplink slot i for serving cell c is given

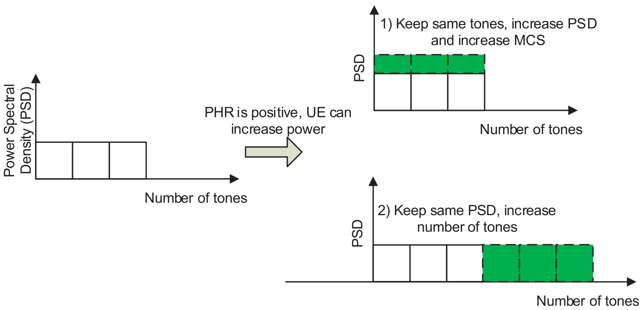

FIGURE 5. Illustration of power control.

by [21] [22]: if the number of repetitions of the allocated NPUSCH RUs is less than 2,

$$P_{\mathrm{NPUSCH,c}}(i) = \min\{P_{\mathrm{CMAX,c}}(i), 10\log_{10}(M_{\mathrm{NPUSCH,c}}(i)) + P_{\mathrm{O\_NPUSCH,c}}(j) + \alpha_c(j)PL_c\},$$

otherwise,

$$P_{\mathrm{NPUSCH,c}}(i) = P_{\mathrm{CMAX,c}}(i).$$

$P_{\mathrm{CMAX,c}}(i)$ is the configured UE transmit power in NB-IoT uplink slot i for serving cell c, $M_{\mathrm{NPUSCH,c}}(i)$ values are $\{1/4, 1, 3, 6, 12\}$, and $P_{\mathrm{O\_NPUSCH,c}}(j)$ is a parameter composed of the sum of a component $P_{\mathrm{O\_NOMINAL\_NPUSCH,c}}(j)$ provided from higher layers and a component $P_{\mathrm{O\_NOMINAL\_NPUSCH,c}}(j)$ provided by higher layers for serving cell c, where $j = \{1, 2\}$.

$$P_{\mathrm{O\_NPUSCH,c}}(j) = P_{\mathrm{O\_UE\_NPUSCH,c}}(j) + P_{\mathrm{O\_NOMINAL\_NPUSCH,c}}(j),$$

when $j = 1$, $P_{\mathrm{O\_UE\_NPUSCH,c}}(1)$ and $P_{\mathrm{O\_NOMINAL\_NPUSCH,c}}(1)$ are configured by higher layers, where $j = 1$ is used for NPUSCH data (re)transmissions. When $j = 2$, which is used for NPUSCH (re)transmissions corresponding to the random access response grant, $P_{\mathrm{O\_UE\_NPUSCH,c}}(2) = 0$ and $P_{\mathrm{O\_NOMINAL\_NPUSCH,c}}(2) = P_{\mathrm{O\_PRE}} + \Delta_{\mathrm{PREAMBLE\_Msg3}}$, where the parameters $P_{\mathrm{O\_PRE}}$ and $\Delta_{\mathrm{PREAMBLE\_Msg3}}$ are signaled from higher layers for serving cell c. For $j = 1$, $\alpha_c(j)$ is configured by higher layers, and $\alpha_c(j) = 1$ for $j = 2$. For NPUSCH transmitting ACK/NACK, $\alpha_c(j) = 1$. PL_c is the downlink path loss estimate calculated in the UE for serving cell c. eNB shall schedule the correct tones and MCS according to the received Power Header Room (PHR) report; otherwise, power scaling in the UE side may occur. As shown in Fig. 5, when PHR is positive, it means that UE can increase power in the next round of transmission. There are two methods for eNB to select: the first is to increase the Power Spectral Density (PSD) and MCS, and the second is to select a larger number of tones. Therefore, eNB will make wrong MCS increasing and tone selection if UE has used maximum power and eNB has not received UE's PHR report.

In NB-IoT, NB-PHR is computed using [21] [22]:

$$PH_c(i) = P_{\mathrm{CMAX,c}}(i) - \{P_{\mathrm{O\_UE\_NPUSCH,c}}(1) + \alpha_c(1) \cdot PL_c\},$$

where $P_{\mathrm{CMAX,c}}(i)$, $P_{\mathrm{O\_UE\_NPUSCH,c}}(1)$, $\alpha_c(1)$ and PL_c are defined as above. There will be 4 reportable values of $[PH1, PH2, PH3, PH4]$ dB. Therefore, eNB can schedule the correct RU and MCS according to PH_c and the repetition number.

b: UPLINK TRANSMISSION GAP

Note that the delay target of 10 seconds is mentioned in 3GPP [23] as appropriate for NB-IoT, measured at the application layer from the UE to the S1 interface. It needs to introduce uplink transmission gaps for long uplink (i.e., NPUSCH/NPRACH) transmissions. During uplink transmission gaps, the UE may switch to the downlink and perform time/frequency synchronization. The uplink transmission gap is defined by a period X and a gap length Y. A minimum period $X_{\min}$ is defined in the specifications [20], and $Y > 0$. All uplink transmissions with a duration greater than or equal to X ms apply a transmission gap with gap length Y and periodicity X until the uplink transmission completes. For NPUSCH, $X = 256$ ms and $Y = 40$ ms. For NPRACH, $X = 64 *$ (preamble duration), and $Y = 40$ ms. In our uplink scheduling algorithm, we should take this transmission gap into account.

2) APPLICATIONS AND OPEN ISSUES

The NB-IoT, interconnection and communication between everyday objects, enables many applications in many domains. The application domain of NB-IoT can be divided into three main categories based on their focus: industry, environment, and society. Supply chain management, transportation and logistics, aerospace, aviation, and automotive are some of the industry-focused applications of NB-IoT. Telecommunication, medical technology, healthcare, smart building, home and office, media, entertainment, and ticketing are some of the society-focused applications of NB-IoT. Agriculture and breeding, recycling, disaster alerting, and environmental monitoring are some of the environment-focused applications. The applications mainly include smart cities, smart environment, smart water, smart metering, security and emergencies, retail, logistics, industrial control, smart agriculture, smart animal farming, domestic and home automation, and eHealth. Fig. 6 shows some of the main applications of NB-IoT. The vehicles, monitors and meters equipped with NB-IoT connectivity will grow up quickly after NB-IoT systems roll out in 2017. NB-IoT and other Lower Power Wide Area (LPWA) sytems will occupy 14% of connections in 2024 according to Machina Research estimation. Because of the diversity of NB-IoT applications, it can combine with extensive other technologies, such as cognitive radio, energy harvesting, and device-to-device (D2D) communications, among others.

Since NB-IoT is a very new technology specifically designed for IoT, it has many open issues to explore. We briefly provide the following examples.

- *Standardization activity:* Since NB-IoT is a very emerging technology specific for IoT systems, the related standardization activity about it is currently incomplete. Several contributions to the full deployment and standardization of the NB-IoT paradigm are needed for the scientific community.

- *Heterogeneity:* One of the main characteristics of NB-IoT is its ability to integrate many types of devices, technologies, and services. NB-IoT systems should support a large variety of different applications whose requirements may be extremely diverse, in terms of bandwidth, latency, reliability, and so forth. These heterogeneity traits of the system make the design of a unifying framework a very challenging task.
- *Security and privacy:* One major social concern related to NB-IoT systems is security and privacy. In NB-IoT systems, in addition to the obvious weakness of the radio channel with regard to eavesdropping, the heavily constrained nature of the devices and the limited available bandwidth make it very challenging to provide effective security mechanisms via simple algorithms with limited room for message exchanges.
- *Energy management:* Energy management, including harvesting, conservation and consumption, in NB-IoT systems is a major issue. Because of the very reduced bandwidth and considerably more complicated channel conditions for NB-IoT systems, the current power control technology is inadequate and the existing processing power and energy capacity are too low to meet future needs. The development of new and more efficient energy management technology will be the key factor for the roll out of future wireless smart systems.

C. LINK ADAPTATION

To improve the system capacity, peak data rate, and coverage reliability, LTE supports channel-dependent link adaptation, which is the adaptation of transmission settings (i.e., MCS and PRB) to the radio channel conditions. Based on periodic or aperiodic feedback from the UE regarding its channel qualities, eNB can select a transmission MCS level, as well as the resources (i.e., PRB) to allocate to the UE, to ensure that UEs can decode it with a transport BLER not exceeding 10% and achieve maximum throughput.

In the specification, an MCS table is utilized for the MCS determination. By reading the MCS index, UEs could derive the modulation scheme. Furthermore, combining the MCS level index and PRB allocation information, the size of the transmitted data can be obtained and the code rate can be calculated accordingly.

D. PROBLEM STATEMENT

With the support of repetition, link adaptation for NB-IoT systems should be conducted in at least two dimensions: the MCS level selection and the repetition number determination. Hence, existing LTE based link adaptation scheme can not be utilized any more. It's crucial to design a new link adaptation scheme for NB-IoT by further considering the repetition.

Furthermore, we should try all potential combinations of MCS level and repetition number and then select an optimal combination for certain channel status if we want to get the global optimal combination. It is obviously difficult to achieve or with high complexity, which violates the low-complexity feature for NB-IoT when performing the link adaptation. Besides, there may exist many potential combinations of MCS level and repetition number that satisfy the transmission BLER. To this end, we focus on designing a low-complexity uplink link adaptation scheme specific to NB-IoT systems in this paper.

Two possible uplink link adaptation schemes with low complexity might exist. The first one is the *MCS-dominated* approach, in which we first adjust the MCS level based on feedback signals and then adjust the repetition number. The second one is the *repetition-dominated* approach, in which we first determine the repetition number and then focus on selecting the MCS level based on the currently determined repetition number. Our link-level simulations in Section IV demonstrate that the first scheme is better than the second. Therefore, in the next section, we focus on introducing the first scheme.

III. PROPOSED UPLINK LINK ADAPTATION FOR NB-IoT

In this section, we formally propose our designed uplink link adaptation scheme for NB-IoT systems. Our proposed uplink link adaptation scheme includes the inner loop link adaptation and the outer loop link adaptation. In particular, the outer loop link adaptation is composed of MCS level selection and repetition number determination.

A. INNER LOOP LINK ADAPTATION

Since the channel conditions of NB-IoT systems are considerably more complicated than conventional LTE systems, the transmission BLER may rapidly change in NB-IoT systems. Therefore, in this subsection, we propose the inner loop link adaptation as an additional link adaptation method to cope with the fast transmission BLER variation. It works as follows: in one period T, all transmission ACK/NACKs are calculated as BLER, and the inner loop link adaptation adjusts the repetition number for this transmission at the expired time of period T based on the current transmission BLER. Specifically, in LTE systems, the evaluation period of BLER (i.e., T) is approximately tens ms, whereas it is approximately hundreds of ms in NB-IoT systems, i.e., 300 ms. If the current BLER is less than 7%, we decrease the repetition number for this transmission; however, if the current BLER is greater than 13%, then we increase the repetition number.[4]

B. OUTER LOOP LINK ADAPTATION

1) MCS LEVEL SELECTION

The LTE systems increase the MCS level if it successively decodes a certain number of ACKs and decrease the MCS

[4]Since our purpose of link adaptation is to keep transmission BLER around 10% according to [22], we use 7% and 13% as thresholds for the inner loop link adaptation whose purpose is to periodically adjust the real-time transmission BLER based on the ACK/NACKs. Furthermore, these two thresholds are empirical values through our extensive link level simulations, and in LTE system there also exist these two empirical values when performing link adaptation.

FIGURE 6. Illustration of applications for NB-IoT.

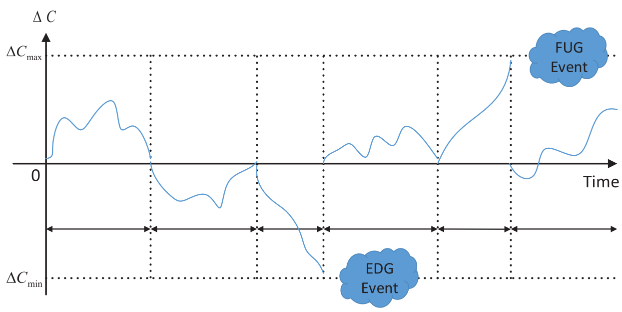

FIGURE 7. Illustration of FUG and EDG.

TABLE 1. Relationship between MCS level, resource unit (RU), and transmit block size (TBS). Note that for single-tone transmission, MCS levels 11 and 12 cannot be achieved.

MCS	Number of resource units							
	1	2	3	4	5	6	8	10
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	680
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1000
7	104	224	328	472	584	712	1000	
8	120	256	392	536	680	808		
9	136	296	456	616	776	936		
10	144	328	504	680	872	1000		
11	176	376	584	776	1000			
12	208	440	680	1000				

level if it successively decodes a certain number of NACKs. Generally, the number of ACKs is more than that of NACKs to ensure a slow increase of the MCS level with ACK feedback and quick decrease of the MCS level with NACK feedback. Because of the narrowband and low data rate for NB-IoT systems, the settings for LTE systems might no longer be applicable. Specifically, we define two aperiodic and event-triggered actions of MCS: *fast upgrade (FUG)* and *emergency downgrade (EDG)*. When the FUG action occurs, we increase MCS by one, and when the EDG action occurs, we decrease MCS by one. Furthermore, we will reset the BLER once an event (FUG or EDG) has been detected. To precisely quantify the FUG and EDG actions, we introduce a compensation factor $\Delta C(t)$ whose upper and lower limits are $\Delta C_{\max}$ and $\Delta C_{\min}$, respectively. Fig. 7 provides an illustration of trigger event FUG and EDG. FUG shall be triggered whenever the compensation value ΔC reaches the value of $\Delta C_{\max}$, and EDG shall be triggered whenever the compensation value ΔC reaches the value of $\Delta C_{\min}$.

During each uplink transmission, we perform the following calculation regarding $\Delta C(t)$ according to uplink transmission HARQ feedback:

$$\Delta C(t) = \begin{cases} \min\{\Delta C(t-1) + C_{\text{stepup}}, \Delta C_{\max}\}, \\ \qquad \text{if HARQ feedback} = \text{ACK}; \\ \max\{\Delta C(t-1) - C_{\text{stepdown}}, \Delta C_{\min}\}, \\ \qquad \text{if HARQ feedback} = \text{NACK}; \\ \Delta C(t-1), \\ \qquad \text{if HARQ feedback} = \text{N/A}. \end{cases}$$

where C_{stepup} and C_{stepdown} are incremental compensation step sizes, which obey the following formula:

$$C_{\text{stepdown}} = C_{\text{stepup}} \frac{1 - \text{BLER}_{\text{target}}}{\text{BLER}_{\text{target}}}.$$

N/A means discontinuous transmission (DTX), i.e., eNB does not detect the NPUSCH signal.

Based on the above, we can continuously update the MCS level based on the compensation value ΔC. Furthermore, for each updated MCS level, we can determine the resource unit based on Table 1 by using a look-up table method. For example, when the transmission size is 600 and the current MCS level is 5, the resource unit should be 8 according to Table 1.

2) REPETITION NUMBER DETERMINATION

In this subsection, we continue to determine the repetition number to guarantee the transmission reliability (i.e., BLER less than 10%). The repetition number is strongly influenced by the channel status and the previously determined MCS level. For example, when the channel is bad and the selected MCS can not support the target BLER, we need to increase the repetition number. However, when the channel is relatively good and the selected MCS yields a BLER under 10%, we need to decrease the repetition number. Fig. 8 presents an example of the variation of the MCS level and repetition number when the UE moves from the cell center to the cell border and then moves back to the center. This figure shows

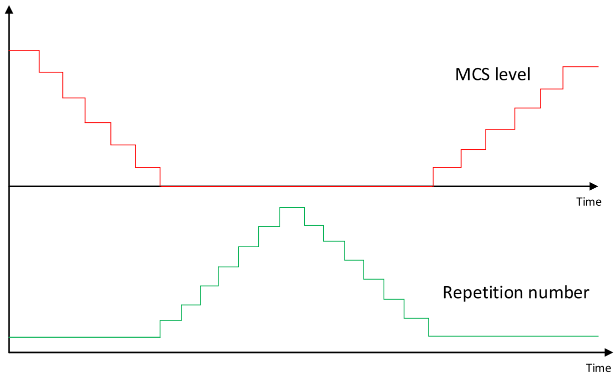

FIGURE 8. **Variation of MCS level and repetition number.**

that the number of repetitions changes only when we have to adjust the MCS level first.

C. PROPOSED ALGORITHM (NBLA)

Algorithm (NBLA) (please notice that "NBLA" stands for NarrowBand Link Adaptation) shows the details of the proposed uplink link adaptation scheme for NB-IoT systems. It contains two phases: inner loop link adaptation and outer loop link adaptation. The purpose of inner loop link adaptation is to guarantee the transmission BLER by adjusting the repetition number in lines 2-8. Furthermore, outer loop link adaptation is given in lines 9-50. It mainly contains three cases based on the different values of MCS: minimum MCS level (i.e., $L = L^{\min}$), maximum MCS level (i.e., $L = L^{\max}$) and medium MCS level (i.e., $L^{\min} < L < L^{\max}$).

- If $L^{\min} < L < L^{\max}$, we first update the compensation value ΔC based on feadback signals ACK/NACKs in lines 10-14. Then, we check the actions FUG and EDG and update the MCS level accordingly in lines 15-19. It is obvious that in the medium MCS level case, we only adjust the MCS level but without any operation for repetition number.
- If $L = L^{\min}$ and the feedback is ACK, we focus on adjusting the MCS level if the current repetition number $N = N^{\min}$ in lines 22-26, and we decrease the repetition number by half if $N > N^{\min}$ in lines 27-29. However, if the feedback is NACK, we double the repetition number if $N < N^{\max}$. Moreover, if $N = N^{\max}$, this means that the channel condition is extremely bad in lines 31-35.
- If $L = L^{\max}$ and the feedback is ACK, we decrease the repetition number by half if $N > N^{\min}$; if $N = N^{\min}$, this means that the channel condition is extremely good in lines 38-43. However, if the feedback is NACK, we focus on adjusting that MCS level in lines 44-48.

IV. SIMULATION RESULTS

In this section, link level simulations are performed to validate the performance of our proposed Algorithm 1 uplink link adaptation scheme for NB-IoT systems.

Algorithm 1 (NBLA): Proposed Uplink Link Adaptation Algorithm for NB-IoT Systems

1: **Initialization:** $\mathrm{BLER}_{\mathrm{target}} = 10\%$, $C_{\mathrm{stepup}} = 0.2$, $C_{\mathrm{stepdown}} = C_{\mathrm{stepup}} \frac{1-\mathrm{BLER}_{\mathrm{target}}}{\mathrm{BLER}_{\mathrm{target}}}$, $\Delta C = 0$, $\Delta C_{\max} = +5$, $\Delta C_{\min} = -5$, MCS level L and its bounds $L^{\max}$, $L^{\min}$, repetition number N and its bounds $N^{\max}$, $N^{\min}$. We empirically initialize the MCS level and repetition number based on the channel condition.
2: **if** period T expired out **then**
3:   **if** $BLER < 7\%$ **then**
4:     $N = N/2$.
5:   **else if** $BLER > 13\%$ **then**
6:     $N = 2N$.
7:   **end if**
8: **end if**
9: **if** $L > L^{\min}$ & $L < L^{\max}$ **then**
10:   **if** HARQ feedback = ACK **then**
11:     $\Delta C = \min\{\Delta C + C_{\mathrm{stepup}}, \Delta C_{\max}\}$.
12:   **else if** HARQ feedback = NACK **then**
13:     $\Delta C = \max\{\Delta C - C_{\mathrm{stepdown}}, \Delta C_{\min}\}$.
14:   **end if**
15:   **if** $\Delta C = \Delta C_{\max}$ **then**
16:     $L = L + 1$.
17:   **else if** $\Delta C = \Delta C_{\min}$ **then**
18:     $L = L - 1$.
19:   **end if**
20: **else if** $L = L^{\min}$ **then**
21:   **if** HARQ feedback = ACK **then**
22:     **if** $N = N^{\min}$ **then**
23:       $\Delta C = \min\{\Delta C + C_{\mathrm{stepup}}, \Delta C_{\max}\}$.
24:       **if** $\Delta C = \Delta C_{\max}$ **then**
25:         $L = L + 1$.
26:       **end if**
27:     **else if** $N > N^{\min}$ **then**
28:       $N = N/2$.
29:     **end if**
30:   **else if** HARQ feedback = NACK **then**
31:     **if** $N = N^{\max}$ **then**
32:       the current channel condition is extremely bad.
33:     **else if** $N < N^{\max}$ **then**
34:       $N = 2N$.
35:     **end if**
36:   **end if**
37: **else if** $L = L^{\max}$ **then**
38:   **if** HARQ feedback = ACK **then**
39:     **if** $N = N^{\min}$ **then**
40:       the current channel condition is extremely good.
41:     **else if** $N > N^{\min}$ **then**
42:       $N = N/2$.
43:     **end if**
44:   **else if** HARQ feedback = NACK **then**
45:     $\Delta C = \max\{\Delta C - C_{\mathrm{stepdown}}, \Delta C_{\min}\}$.
46:     **if** $\Delta C = \Delta C_{\min}$ **then**
47:       $L = L - 1$.
48:     **end if**
49:   **end if**
50: **end if**

TABLE 2. Parameter settings.

System bandwidth	200 kHz
Carrier frequency	900 MHz
Subcarrier spacing	15 kHz
Channel coding for NPDCCH	Tail biting convolution code
Channel estimation for NPDCCH	DMRS-based
Aggregation level for NPDCCH	2 NCCE
Channel coding for NPUSCH	Turbo codes
Interference Rejection Combiner	MRC
Number of Tx antennas	1
Number of Rx antennas	2
Number of tones	1
Frequency offset	200 Hz
Time offset	2.5 us
Channel model	AWGN

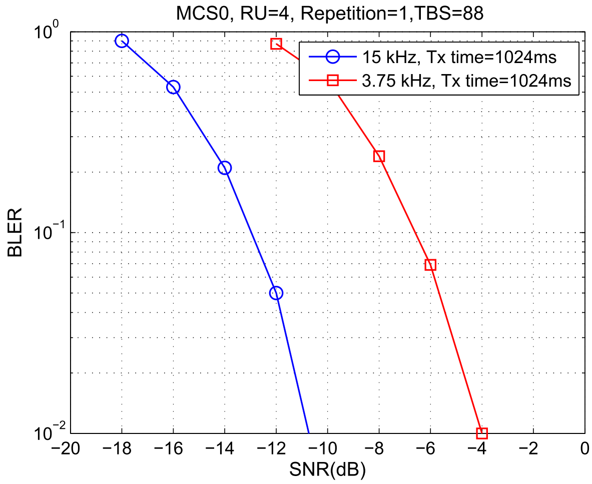

FIGURE 9. Relationship between BLER and SNR when MCS0, RU=4, and repetition=1.

A. PARAMETER SETTINGS AND METRICS

To evaluate the performance of the proposed uplink link adaptation scheme for NB-IoT, we set the system parameters as listed in Table 2 for our simulations.

Transmission time and resource utilization are the main concerns in our simulations, low transmission time and high resource utilization rate can improve throughput of NB-IoT systems. To this end, we use the active time and consumed resources for transmitting a whole packet as the evaluation metrics. Active time is defined as the summation of transmission time for both NPDCCH and NPUSCH. More transmit power will be consumed with a longer active time. Therefore, the active time could reflect the power consumption. Furthermore, consumed resources are the consumed resources for NPUSCH. More consumed resources lower the spectral efficiency. Thus, it could represent the spectral efficiency performance.

B. SIMULATION RESULTS

1) PERFORMANCE EVALUATION

Fig. 9 and Fig. 10 show the relationship between BLER and Signal-to-Noise Ratio (SNR) with different simulation settings for NPUSCH single tone. The results show that BLER deceases with as the receive SNR increases (i.e., channel condition is better). Moreover, from the results in Fig. 9 and Fig. 10, we can observe that when we receive ACK/NACK for a particular MCS level, RU and repetition settings. For example, when MCS=0, RU=4 and repetition=1 for 15 kHz spacing single tone, we can receive ACK when the SNR is larger than −13 dB.

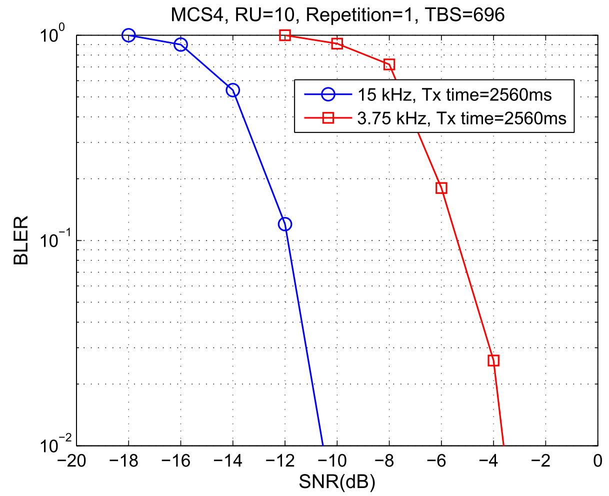

FIGURE 10. Relationship between BLER and SNR when MCS4, RU=10 and repetition=1.

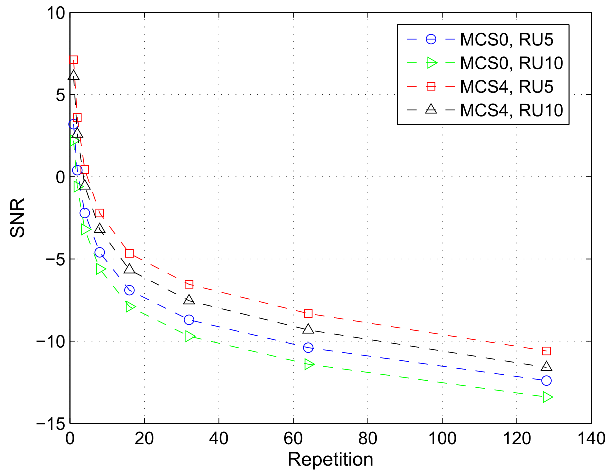

FIGURE 11. Relationship between SNR and repetition with different numbers of RUs.

Furthermore, Fig. 11 shows the relationship between SNR and repetition with different numbers of RUs. The results show that when we use a larger number of repetition, we can correctly decode the message with worse channel conditions. In addition, it can be observed that a message can be transmitted successfully with worse channel conditions when we use a larger number of RUs.

2) PERFORMANCE ENHANCEMENT

Based on the extensive link-level simulation results as shown in Fig. 9, Fig. 10, and Fig. 11, we continue to demonstrate the performance advantages of our proposed uplink link adaptation scheme (denoted as NBLA) in Fig. 12 and Fig. 13. For comparison, we use a straightforward method (denoted as straightforward) and repetition-

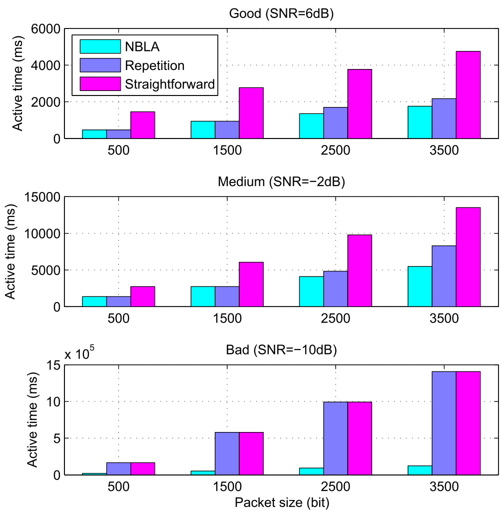

FIGURE 12. **Active time comparison between proposed scheme, repetition-dominated method, and straightforward method.**

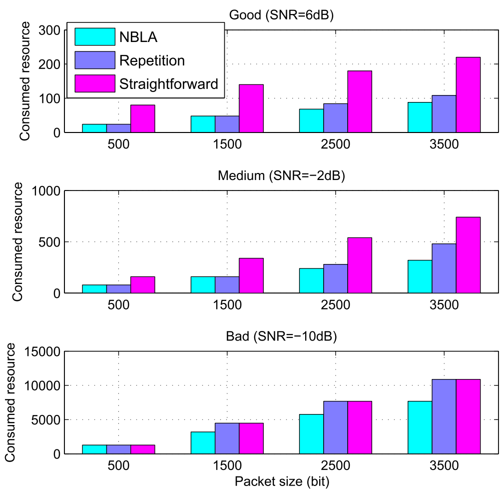

FIGURE 13. **Consumed resource comparison between proposed scheme, repetition-dominated method, and straightforward method.**

dominated method (denoted as repetition). In the straightforward method, we always set the MCS level as 0 and use the maximum RU to transmit the packet, and based on the channel status, we adjust the repetition number only. In the repetition-dominated method, based on the feedback ACK/NACKs, we first adjust the repetition number and then update the MCS level. In particular, we vary the packet size $\{500, 1500, 2500, 3500\}$ bits and test three cases of channel conditions based on the channel estimation of NB-IoT systems: good (SNR=6 dB), medium (SNR=−2 dB), and bad (SNR=−10 dB).

Figs. 12 and 13 show the active time and consumed resources, respectively, of the proposed uplink link adaptation scheme, repetition-dominated method, and straightforward method. The results in Fig. 12 and Fig. 13 demonstrate that our proposed uplink link adaptation scheme outperforms the repetition-dominated method and straightforward method. Specifically, our proposed uplink link adaptation scheme can on average save 14.29% of active time and 14.01% of resource consumption compared to the repetition-dominated method. Moreover, it can on average save 47.18% of active time and 46.35% of resource consumption compared to the straightforward method. The reason is that our proposed uplink link adaptation scheme can adaptively select the MCS level and repetition number with different channel conditions in comparison with the straightforward method. Furthermore, our proposed uplink link adaptation scheme focuses on selecting the MCS level first, which is more important than the repetition number in terms of spectral efficiency. Therefore, it outperforms the repetition-dominated method.

Moreover, some insights are presented in Fig. 12 and Fig. 13: 1) More active time and resources can be saved when the packet size is larger. This is because for larger packets, our proposed uplink link adaptation scheme can select larger TBS, which thus reduces the active time and consumed resources; and 2) When the channel conditions are better, our proposed uplink link adaptation scheme can also save more active time and resources. This is because it can select a larger MCS level (thus with a larger TBS) to save active time and consumed resources.

V. CONCLUSION

In this paper, we provide a brief survey of NB-IoT, including protocol volume, key technologies of uplink scheduling, applications, and several open issues. Based on these factors, we design a novel uplink link adaptation for NB-IoT systems that contains the inner loop link adaptation and the outer loop link adaptation to guarantee the transmission BLER. The inner loop link adaptation is proposed to cope with the fast BLER variation by adjusting the repetition number based on periodically measured transmission BLER. Moreover, the outer loop link adaptation includes MCS level selection and repetition number determination. It first determines the MCS level based on the feedback signals ACK/NACKs and then determines the repetition number. Extensive link-level simulations are provided to validate the performance of our proposed uplink link adaptation scheme for NB-IoT systems. The results demonstrate that our proposed uplink link adaptation scheme can on average save more than 14% of active time and resource consumption in comparison with the repetition-dominated method and save more than 46% of active time and resource consumption in comparison with the straightforward method.

In the future, we will conduct a performance analysis and setup system-level simulations of uplink link adaptation for NB-IoT systems.

REFERENCES

[1] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[2] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Context aware computing for the Internet of Things: A survey," *IEEE Commun. Surveys Tut.*, vol. 16, no. 1, pp. 414–454, 1st Quart., 2014.

[3] F. Liu, C. Tan, E. Lim, and B. Choi, "Traversing knowledge networks: An algorithmic historiography of extant literature on the Internet of Things (IoT)," *J. Manage. Anal.*, pp. 1–32, Aug. 2016, doi: 10.1080/23270012.2016.1214540.

[4] L. D. Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.
[5] S. Li, L. D. Xu, and S. Zhao, "The Internet of Things: A survey," *Inf. Syst. Frontiers*, vol. 17, no. 2, pp. 243–259, 2015.
[6] 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.
[7] *Introduction of NB-IoT in 36.331*, 3GPP RP-161248, 3GPP TSG-RAN Meeting 72, Ericsson, Nokia, ZTE, NTT DOCOMO Inc., Busan, South Korea, Jun. 2016.
[8] Stubbs Agnes, "Intel, Nokia and Ericsson Collaborate on NB-LTE Wireless for IoT," Capacity Magazine, Helsinki, Finland, Oct. 2015, pp. 1–5.
[9] Y.-P. E. Wang *et al.* (Jul. 2016). "A primer on 3GPP narrowband Internet of Things (NB-IoT)." [Online]. Available: https://arxiv.org/ftp/arxiv/papers/1606/1606.04171.pdf
[10] A. Sampath, P. Sarath Kumar, and J. M. Holtzman, "On setting reverse link target SIR in a CDMA system," in *Proc. IEEE Veh. Technol. Conf.*, vol. 2. 1997, pp. 929–933.
[11] Q. Li, Y. Wu, S. Feng, P. Zhang, and Y. Zhou, "Cooperative uplink link adaptation in 3GPP LTE heterogeneous networks," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.
[12] A. Durán, M. Toril, F. Ruiz, and A. Mendo, "Self-optimization algorithm for outer loop link adaptation in LTE," *IEEE Commun. Lett.*, vol. 19, no. 11, pp. 2005–2008, Nov. 2015.
[13] Q. Xia, M. Hamdi, and K. B. Letaief, "Open-loop link adaptation for next-generation IEEE 802.11n wireless networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3713–3725, Sep. 2009.
[14] A. M. Cavalcante, E. B. Souza, J. J. Bazzo, M. J. Souza, L. Kuru, and J. Moilanen, "On the system-level analysis of outer loop link adaptation for IEEE 802.16e systems," *J. Commun. Comput.*, vol. 9, no. 5, pp. 568–575, 2012.
[15] M. G. Sarret, D. Catania, F. Frederiksen, A. F. Cattoni, G. Berardinelli, and P. Mogensen, "Dynamic outer loop link adaptation for the 5G centimeter-wave concept," in *Proc. Eur. Wireless*, 2015, pp. 1–6.
[16] F. Blanquez-Casado, G. Gomez, M. del Carmen Aguayo-Torres, and J. T. Entrambasaguas, "eOLLA: An enhanced outer loop link adaptation for cellular networks," *EURASIP J. Wireless Commun. Netw.*, no. 1, Dec. 2016.
[17] Q. Mu, L. Liu, H. Jiang, K. Takeda, and R. Ma, "Investigation on link adaptation for LTE-based machine type communication," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.
[18] X. Lin, A. Adhikary, and Y.-P. E. Wang, "Random access preamble design and detection for 3GPP narrowband IoT systems," *IEEE Commun. Lett.*, vol. 5, no. 6, pp. 640–643, Dec. 2016.
[19] *User Equipment (UE) Radio Transmission and Reception*, 3GPP TS 36.101, 2016. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.101/36101-d40.zip
[20] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation*, 3GPP TS 36.211, 2016. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.211/36211-d20.zip
[21] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures*, 3GPP TS 36.213, 2016. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.211/36213-d20.zip
[22] *Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and Channel Coding*, 3GPP TS 36.212, 2016. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.211/36212-d20.zip
[23] *Cellular System Support for Ultra Low Complexity and Low Throughput Internet of Things*, 3GPP TR 45.820 v13.1.0, Nov. 2015. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/45_series/45.820/45820-d10.zip

CHANGSHENG YU (M'15) received the master's degree from Zhejiang University, Hangzhou, China, in 2005, and the Ph.D. degree in control science and engineering from Zhejiang University of Technology, Hangzhou, China, in 2013.

He was with the Nokia Wireless Network Department, where he researched and developed the algorithm for MAC scheduler for LTE/LTE-A and recent NB-IoT protocol analysis. His major interests focus on 5G, heterogeneous networks, and the IoT network.

LI YU received the B.S. degree in control theory from Nankai University, Tianjin, China, in 1982, and the M.S. and Ph.D. degrees in control theory from Zhejiang University, Hangzhou, China, in 1988 and 1999, respectively.

He is currently a Professor with the College of Information Engineering, Zhejiang University. He has authored or co-authored three books and more than 200 journal or conference papers. His research interests include wireless sensor networks, networked control systems, and motion control.

YUAN WU received the Ph.D. degree in electronic and computer engineering from The Hong Kong University of Science and Technology, Hong Kong, in 2010.

He was a Post-Doctoral Research Associate with The Hong Kong University of Science and Technology from 2010 to 2011. He was a Visiting Scholar with Princeton University, Princeton, NJ, USA, from 2009 to 2010, Georgia State University, USA, in 2013, and the University of Waterloo, Canada, from 2016 to 2017. He is currently an Associate Professor with the College of Information Engineering, Zhejiang University of Technology, Hangzhou, China. His research interests focus on radio resource allocations for wireless communications and networks, cognitive radio networks, data offloading, device-to-device communications, and smart grids.

Prof. Wu received the Distinguished Young Faculty Award from Zhejiang University of Technology in 2013, and the scholarship under the State Scholarship Fund of China Scholarship Council for Visiting Scholars in 2015. He was a co-recipient of the Second-Class Outstanding Research Award for Zhejiang Provincial Universities in 2012.

YANFEI HE is currently pursuing the M.S. degree with the College of Information Engineering, Zhejiang University of Technology, Hangzhou, China. His research interests focus on radio resource allocations for wireless communications and networks and mobile data offloading networks.

QUN LU received the B.S. degree in mechanical engineering from the Yancheng Institute of Technology in 2011 and the M.S. degree in 2013. He is currently pursuing the Ph.D. degree in control science and engineering. His major interests focus on wireless sensor network, computer vision, robot control, and machine learning.