Smart Choice for the Smart Grid: Narrowband Internet of Things (NB-IoT)

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***Abstract*—The low power wide area network (LPWAN) technologies, which is now embracing a booming era with the development in the Internet of things (IoT), may offer a brand new solution for current smart grid communications due to their excellent features of low power, long range, and high capacity. The mission-critical smart grid communications require secure and reliable connections between the utilities and the devices with high quality of service (QoS). This is difficult to achieve for unlicensed LPWAN technologies due to the crowded license-free band. Narrowband IoT (NB-IoT), as a licensed LPWAN technology, is developed based on the existing LTE specifications and facilities. Thus, it is able to provide cellular-level QoS, and henceforth can be viewed as a promising candidate for smart grid communications. In this paper, we introduce NB-IoT to the smart grid and compare it with the existing representative communication technologies in the context of smart grid communications in terms of data rate, latency, and range, etc. The overall requirements of communications in the smart grid from both quantitative and qualitative perspectives are comprehensively investigated and each of them is carefully examined for NB-IoT. We further explore the representative applications in the smart grid and analyze the corresponding feasibility of NB-IoT. Moreover, the performance of NB-IoT in typical scenarios of the smart grid communication environments, such as urban and rural areas, is carefully evaluated via Monte Carlo simulations.**

***Index Terms*—Advanced metering infrastructure (AMI), communication technologies, LPWAN, NB-IoT, smart grid**

I. Introduction

THE Internet of things (IoT), as revealed by its name, denotes the concept that every object is connected and has the capability of sending and receiving data. The key element to enable the IoT paradigm is the seamless integration of potentially any object with the Internet, which creates new forms of interaction between human and devices, as well as among devices themselves, which is commonly referred to as the machine-to-machine (M2M) communications [1]. The IoT, or M2M in particular, scenarios are considered as major challenges for the next generation wireless cellular systems, since most of the IoT services are expected to generate a relatively small amount of traffic and lower power consumption from a very large number of devices, whereas current cellular communication architectures are designed for wideband services aiming for higher data rate and spectral efficiency [2]. Thus, the shift of paradigm urgently calls for a new breed of wireless technologies to consummate the 5th generation mobile networks (5G) [3].

Recently, a new wireless technology called low power wide area network (LPWAN), due to its long-range, low-power, and low-cost communication capability, has gained unprecedented momentum and commercial interest from both the academia and the industry [4]. It is now widely considered as the future wireless communication standard for IoT. LPWAN technologies can perfectly serve most IoT applications with the abilities to offer a large scale of coverage and a massive capacity of supporting millions of devices per cell, as well as long battery life of up to 10 years. Cisco estimates that the market of LPWAN is expected to account for 28% of M2M connections by 2020 with a 38% compound annual growth [5]. The breed of LPWAN technologies can be divided into two categories according to their operating frequency bands. One set of LPWAN technologies operates on the unlicensed industrial, scientific and medical (ISM) radio bands, such as LoRa (Long Range) [6] and Sigfox [7]. The other set operates on the licensed bands, such as enhanced machine type communications (eMTC) and narrowband IoT (NB-IoT) [8]. The LPWAN technologies can be applied into many fields of IoT, such as smart city [9], smart building, etc.

The smart gird is a new concept of next generation electric power system, which integrates automated control and modern communications technologies into the electric power grid infrastructure to improve the efficiency, reliability and safety of the conventional electrical power grid [10]. As the smart grid develops, many endeavors started to introduce the IoT as an enabling technology to the smart grid since each device in the grid can be considered as a connected object. The smart grid incorporates a large number of devices/sensors that autonomously report their information to grid infrastructure.

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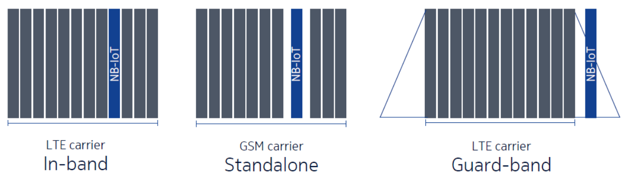

Fig. 1. The deployment options of NB-IoT.

With the help of IoT technologies, power disturbances and outages caused by equipment failures, capacity constraints, etc., can be largely avoided by online power system condition monitoring, diagnosis, and protection. Up to now, there are many technologies that can accommodate the communication needs in the smart grid. For example, wired communications technologies such as fiber optic, digital subscriber line (DSL), and power line communications (PLC) and wireless technologies such as ZigBee, wireless local area networks (WLANs), wireless mesh networks and WiMAX [11], etc. are all possible candidates. Nonetheless, though these solutions allow the connection of the IoT devices in the smart grid, they usually have various disadvantages such as high cost, low scalability, short battery life, high complexity, and low reliability. For instance, the limited coverage of ZigBee as well as the weak diffraction ability of WiMAX become major obstacles if adopted in the smart gird, especially in urban areas. To better satisfy the communication requirements of smart grid, LPWAN technology may provide a brand new solution.

The smart grid is a mission-critical infrastructure, it demands secure and reliable communications with high quality of service (QoS) requirement. It is difficult for license-free LPWAN technologies to fulfill these requirements since they are very likely to suffer from the interference in the crowded unlicensed band. NB-IoT works on the licensed spectrum and is designed based on existing LTE functionalities. It is capable of providing a foundation for long-term service level agreements with a specific grade of service, which cannot be reached by unlicensed technologies. In addition, compared to LoRa and Sigfox, NB-IoT relies on the existing cellular infrastructure instead of new ones, thus the investments on a utility-dedicated communication infrastructure and the time required for deployment of applications is reduced.

NB-IoT now has been standardized by 3rd generation partnership project (3GPP) in long term evolution (LTE) release 13 [12], and has received strong support from Huawei, Ericsson, and Qualcomm. The objectives of NB-IoT are to ensure a device cost below 5 USD, uplink latency below 10 s, up to 40 connected devices per household, a device with 164 dB coupling loss, and a 10-year battery life can be reached if the user equipment (UE) transmits 200 bytes of data a day on average [13]. There are three modes of deployment options for NB-IoT, as shown in Fig. 1: 1) In-band operation, in which NB-IoT is deployed inside a LTE carrier occupying one of the resource blocks (RBs), 2) Guard-band operation, in which NB-IoT is deployed within the guard-band of a LTE carrier and 3) Stand-alone operation, in which NB-IoT can be used in place of one or more GSM carriers. Many papers in the literature have investigated the different features of NB-IoT. A detailed description of the NB-IoT system and an overview of physical and higher layer design were provided in [14]-[16]. The evolution of 3GPP standards related with NB-IoT was described in [8], along with the changes introduced into LTE standards to provide support to NB-IoT. In [17], a deployment study of NB-IoT was discussed. In [18], a prototype system including NB-IoT devices, an IoT cloud platform, and an application server has been proposed. The studies in [19] and [20] are focused on the coverage of NB-IoT. In [21], the applicability of NB-IoT for opportunistic crowdsensing applications with assisting vehicle-mounted relays was investigated in detail. Nevertheless, to the best of the authors' knowledge, there are still plenty of issues be investigated when applying NB-IoT to the smart grid, which motivated our research.

In this paper, we introduce NB-IoT to the smart grid and compare it with existing representative communication technologies in the smart grid. The overall requirements of the smart grid from both quantitative and qualitative perspectives are comprehensively investigated and the performance of NB-IoT is evaluated regarding each of them. The contribution of this paper can be summarized as follows:

- We survey the available communication technologies in the smart grid, including traditional technologies like ZigBee and WiMAX, as well as typical LPWAN technologies such as LoRa and NB-IoT. The key performance indicators of these technologies are investigated in detail, such as data rate, latency, etc.
- We provide a comprehensive assessment of the communication requirements of the smart grid from both quantitative and qualitative perspectives, e.g., data rate, reliability, security, and scalability. Each of these requirements is carefully examined to see whether it can be satisfied by NB-IoT. Furthermore, based on the analysis about the characteristics of NB-IoT and the requirements of the smart grid, promising smart grid applications of NB-IoT, as well as unsuitable ones, are investigated in detail.
- By simulations, we evaluate the performance of NB-IoT operated with different deployments in four typical communication scenarios of the smart grid, i.e., rural area, bad urban area, typical urban area, and hilly terrain area.

The rest of the paper is organized as follows. In Section II, an overview of available communication technologies is presented. Section III describes the overall requirements of smart grid applications. Section IV gives some examples of applications suitable for NB-IoT. Section V shows the bit error ratio (BER) performance of NB-IoT under different scenarios in the smart grid. Section VI concludes the paper.

II. Available Communication Technologies in Smart Grids

There are many of communication technologies available for smart grids. Communication technologies can be classified into two broad categories: wired and wireless technologies. Wired technologies are usually considered superior to wireless technologies in terms of reliability, security, and bandwidth.

However, wireless communications ensure low installation costs and flexible deployments with minimal cabling, which can provide connectivity over wide areas or areas without pre-existing communication infrastructure. Thus, each of these technologies has its own pros and cons for applications. In this section, we briefly introduce the existing communication technologies in the smart grids and compare them with NB-IoT in terms of performance indicators such as data rate and latency. The results are organized in Table I.

A. Wired Communication Technologies

The representative wired communications technologies are fiber-optic communications, digital subscriber line (DSL) and power line communications (PLC).

Fiber optic offers high data rate up to 40 Gbps, ultra low latency, and high reliability. It is often used to provide backbone communications to transfer the big-amount or real-time information for long distance. However, the deployment and the maintenance of fiber optic networks can be costly.

DSL generally refers to a suite of communication technologies that enable digital data transmission over telephone lines, avoiding the additional cost of deploying the own communication infrastructure of electric utilities. However, the efficiency of DSL declines as the distance increases, as a result it can only operate over short distances (about 1.2 km for VDSL). Moreover, telecom operators can charge utilities high prices to use their networks.

PLC utilizes the existing power cables for data transmission, which reduced the installation cost of the communications infrastructure. Since the signal propagation environment of PLC is harsh and noisy, the channel is difficult to model and the data transmissions via power lines may not be reliable. Nevertheless, thanks to the numerous emerging achievements from both the academia and the industry, the transmission problems are expected to be solved with the rapid development of PLC.

B. Wireless Communication Technologies

ZigBee is a wireless mesh network, built on the IEEE standard 802.15.4 [22]. It is has been widely adopted to smart grid applications due to its low power consumption and low deployment cost. ZigBee operates on the unlicensed ISM bands. The estimated data rates are 250 kbps per channel in the 2.4 GHz band, 40 kbps per channel in the 915 MHz band and 20 kbps per channel in the 868 MHz band. ZigBee is considered as a good option for in-home applications, such as home/building automation, consumer electronics, energy monitoring [23]. There are some constraints on ZigBee in practical use, such as low processing capabilities, small memory size, small delay requirements. Also, since ZigBee shares the license-free spectrum with other appliances, it is more likely subject to interference compared with those licensed technologies.

Wireless Local Area Network (WLAN) is a high-speed wireless Internet and network communication technology, which is commonly known as Wi-Fi. WLAN provides reliable, secure and high-speed communications. The data rate ranges from 2 Mbps to 600 Mbps, and the coverage reaches up to 100 meters [24]. WLAN/Wi-Fi is more suitable for home and local area applications with relatively high data rate requirements, such as video monitoring applications. However, the power consumption of WLAN might be too high for many smart grid devices.

Z-Wave is a reliable, low-power, low-cost proprietary wireless technology operates in the 868 MHz in Europe and 908 MHz ISM band in USA. It has typically 30 m indoor range which extends up to 100 m outdoor and offers a low data rate of 9.6-40 kbps [25]. With the short-range and low-data-rate capabilities, Z-Wave is a good candidate for smart grid applications in home area networks.

WiMAX is a 4G wireless technology based on the IEEE 802.16 series of standards. It provides the data rate up to 75 Mbps, a coverage distance of 50 km, and low latency of 10-50 ms [26]. The WiMAX standard natively supports the real-time high-data-rate two-way broadband communications, such as remote-monitoring, real time pricing, etc,. However, deploying WiMAX can be very expensive since the WiMAX towers are based on relatively costly radio equipments, leading that WiMAX is not widely adopted as a wireless platform for smart grid applications. Furthermore, the frequency of WiMAX higher than 10 GHz results in short wavelength, makes it difficult to pass through obstacles. What is worse, the performance of WiMAX can be even affected by the bad weather conditions. Thus, WiMAX may not the proper candidate for smart grid communications.

Wireless mesh network is a flexible network consisting of a group of nodes, where new nodes is able to join the group and each node acts as an independent router. The self-organization and self-healing characteristics of this topology greatly improve the reliability of network. Wide coverage range and large capacity can be achieved by mesh network due to its ability to perform multi-hop routing. Mesh networks can be implemented with various wireless technologies, i.e., 802.11, 802.15 and 802.16. However, set-up and maintenance of this topology is very difficult. It requires continuous supervision because of the redundancy presented in the network. As a result, a third party company may be needed to maintain and manage the wireless mesh network.

LoRa is a representative unlicensed LPWAN technology operates on the 433-, 868- or 915-MHz ISM bands [27]. It was proposed by Semtech and further promoted by the LoRa Alliance. LoRa is attractive to developers since they can build complete system solutions on the top of it and the specification of the standard LoRaWAN is available free of charge. The modulation of LoRa is based on chirp spread spectrum (CSS) scheme that helps fight against heavy multi-path fading. The coverage of LoRa scales up to 8 km in urban area and 22 km in rural area. It offers the adaptive data rate range from 0.3 to 50 kbps that determined by six orthogonal spreading factors. The low-data-rate characteristic of LoRa determines that it is only applicable to applications with small playloads.

NB-IoT is new 3GPP radio-access technology and designed based on the existing LTE facilities. It can be simply plug into the LTE core network and achieves excellent co-existence performance with legacy GSM, general packet radio service

TABLE I
THE COMPARISON OF COMMUNICATION TECHNOLOGIES IN SMART GRIDS

Technology	Spectrum	Data Rate	Latency	Coverage Range	Cost	Limitation
Wired Communication Technologies						
Fiber Optic	up to 353000 GHz	up to 40 Gbps	3.34 μs per km	up to 100 km	High	High network deployment costs High cost of terminalequipment
DSL	20 kHz-1 MHz	ADSL: 1-8 Mbps HDSL: 2 Mbps VDSL: 15-100 Mbps	10-70 ms	ADSL: up to 5 km HDSL: Up to 3.6 km VDSL: up to 1.2 km	High	Telecom operators can charge utilities high prices to use their networks. Not suitable for network back haul (long distances result into data rate degradation)
PLC	1-30 MHz	2-3 Mbps	5-7 ms	1-5 km	Low	Harsh, noisy channel environment
Wireless Communication Technologies						
ZigBee	2.4 GHz-868-915 MHz	250 kbps	15 ms	30-50m	Low	Short-range
WLAN	2.4 GHz	2-600 Mbps	3.2-17 ms	100 m (indoor)	Low	Power consumption might be too high for many smart grid devices
Z-Wave	2.4 GHz-868-908 MHz	9.6-40 kbps	100 ms	30 m (indoor) 100 m (outdoor)	Low	Short range Low data rate
Wireless Mesh	Various	Depending on selected protocols	Depending on selected protocols	Depending on deployments	High	Network management is complex
WiMAX	2.5 GHz, 3.5 GHz, 5.8 GHz	up to 75 Mbps	10-50 ms	10-50 km (LOS) 1-5 km (NLOS)	High	High cost of terminal equipment Weak diffraction ability
LoRa	868-915-433 MHz	0.3-50 kbps	Average 2 s	3-8 km (urban) 15-22 km (rural) 15-45 km (flat)	Low	Low data rate
NB-IoT	900-1800 MHz	Uplink: $<$ 250 kbps Downlink: $<$ 230 kbps	Less than 10 s	$<$35 km	Low	Latency insensitive

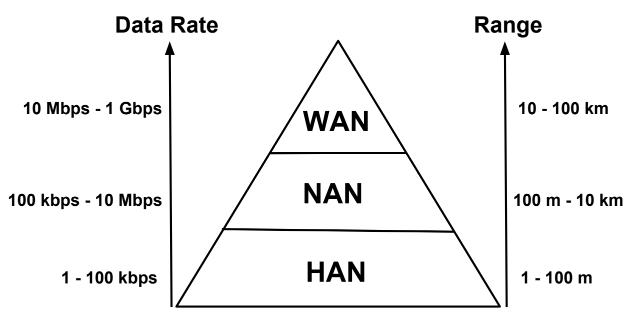

Fig. 2. Date rate and communication range requirements for smart grid communications hierarchy.

(GPRS) and LTE technologies. NB-IoT reuses the LTE design extensively, such as the orthogonal frequency division multiplexing (OFDM) type of modulation in the downlink, single carrier frequency division multiple access (SC-FDMA) in the uplink. The peak data rates of NB-IoT are able to achieve up to 230 kbps for the downlink and 250 kbps for the uplink [14]. However, NB-IoT is a latency insensitive technology, the loose latency character makes it is more applicable to those delay-tolerant applications.

Remarks: In the smart grid environment, a communications network can be classified by data rate and coverage range, presented to be a hierarchical multi-layer architecture, i.e., home area network (HAN), neighborhood area networks (NAN) and wide area network (WAN) [28], as shown in Fig. 2. Based on the aforementioned illustrations, ZigBee, WLAN and Z-Wave are suitable for HAN, fiber optical network and WiMAX for the backbone of WAN, and PLC, DSL, wireless mesh network, LoRa, and NB-IoT can be used in the NAN.

Compared with unlicensed technologies for NAN, NB-IoT is able to provide high QoS and reliable services for mission-critical grid applications. NB-IoT has the similar data rate and latency as wireless mesh networks. The good coverage that NB-IoT achieves can also be provided by wireless mesh networks. Both of them can be applied to many smart grid applications, such as meter reading and home automation. However, wireless mesh networks face many challenges when applied in practice. The loop problems might exist during the data packets travel around many nodes in mesh networks. The redundancy brings additional overheads in the communications channel and would result in wasting of the bandwidth. Also, the security problem of mesh network is serious since the metering information passes through every access point. On the other hand, NB-IoT is believed to be more suitable for smart gird applications. It is developed based on the existing cellular networks, thus widespread, cost-effective communications can be guaranteed. Also, the data flows in cellular network are with strong security controls and its coverage has reached almost 100%, ensuring healthy and secure communications with devices both in rural and urban areas. In addition, NB-IoT employs OFDMA in the downlink and SC-FDMA in the uplink. The multi-user structures of their nature provides massive capacity of the network by allowing simultaneous data transmission from a huge group of users. Moreover, by virtue of the ultra-low-cost feature of NB-IoT ($<$ \$5), NB-IoT is a good choice for large-scale deployment and commercialization in the smart grid.

III. Overall Requirements of Smart Grid Communications

In the following, the major requirements of smart grid communications are presented on two categories: (i) quantitative requirements, which specify in a measurable manner the target communication performance demanded by the smart grid applications, and (ii) qualitative requirements, which identify the capabilities that must be supported by the communication systems.

A. Quantitative Requirements

The key quantitative communication requirements that should be satisfied by the smart grid communications are listed as follows:

- **Latency**: The requirements of latency differ for different smart grid applications. Some mission-critical applications have tight delay constraints and require rapid transmission of information, such as distribution automation deployed in substation (within 4 ms) and wide-area situational awareness systems. For other applications, latency is less critical and higher network delays can be tolerated, such as advanced metering infrastructure (AMI) (e.g., most smart meters send their readings periodically every 15 min per day) or home energy management (HEMs).
  NB-IoT is designed to achieve less than 10 second latency, which determined it is suitable for those latency-insensitive applications. Thus, for applications like sending alarm signals, NB-IoT is not eligible to reach the goal of operating in real-time.
- **Frequency range**: Smart gird applications may need to operate towards the lower end of the frequency spectrum (below 2 GHz) to overcome the line-of-sight issues and provide high-quality and cost-effective communications over the utilities service area.
  Obviously, WiMAX is not eligible for this requirement, whereas NB-IoT is qualified since it shares the same licensed frequency band as 3GPP cellular systems, i.e., 900-1800 MHz.
- **Reliability**: A number of possible causes for network failures, including link/node failures, routing inconsistencies, overloading, etc., lead to the unreliability issues for the smart grid. The system reliability has become one of the most prioritized requirements for power utilities. The communication nodes are supposed to be always reliable for continuity of communications. Some critical smart grid applications, such as distributed automation, require very high level of reliability for data communication. On the other hand, some of applications can tolerate some outages in data transfer.
  Running upon the operators' existing cellular networks on licensed bands provides NB-IoT with higher reliability superiors to that of unlicensed solutions. Moreover, according to 3GPP Release 13, repeating transmission of data or control signals has been selected as a promising approach to enhance the transmission reliability of NB-IoT systems. [29]
- **Date rate**: The data-rate requirements differ for each specific smart grid application. Some of the applications are used to transmit video and audio data, which ask for high date-rate values to accomplish effective data transfer, such as wider-are situational awareness systems. On the other hand, the communication date rate for AMI and distribution automation are typically small (e.g., each meter reading requires about 300 kbps).
  The peak data rate of the downlink for NB-IoT can achieve up to 226.7 kbps and 250 kbps for the uplink. Thus, NB-IoT is especially applicable for the low-data-rate applications, such as AMI. For those applications of high date-rate requirements like video transmission, DSL, WLAN and WiMAX techniques are recommended.

B. Qualitative Requirements

The key capabilities that are necessary for smart grid communications can be summarized as follows:

- **Security**: Smart grid is a critical infrastructure that needs to be robust against failures and attacks. Providing end-to-end security carries the highest priority for almost all smart grid applications [30]. Especially for mission critical applications, such as billing purposes and grid control, security should be provided on a communication network to protect the critical assets of the power grid from any vulnerabilities. For instance, the communication systems must ensure that devices are well protected by physical attacks, unauthorized entities cannot have access to the metering information, or that sensitive data cannot be modified while in transit in the network.
  NB-IoT relies on the cellular networks, whose the security mechanisms have been based on a physical subscriber identification module (SIM) attached to the device. Thus, NB-IoT benefits from all the security and privacy features of cellular networks, which support users identity confidentiality, entity authentication, confidentiality, data integrity, and mobile equipment identification.
- **Scalability**: A smart grid can involve millions of smart meters, smart sensor nodes, smart data collectors, and renewable energy resources, etc. Thus, the scalability is seen as one of the most intuitive requirements for the smart grid communications. There are two perspectives to the define scalability of smart grid, one is load scalability, which means the ability of communication systems to handle an increasing number of devices and the amount of data traffic. The other is geographic scalability, i.e., the ability of the network to deploy in a wide range of sizes and configurations.
  NB-IoT is capable to support of massive low-throughput devices, it aims at supporting at least 52,547 devices per cell and 40 devices per household with only one physical resource blocks (PRB) deployed in cellular system. Evaluations have shown that a standard deployment can support a deployment density of 200,000 NB-IoT devices within a cell (for an activity level corresponding to common use cases), four times better than the initial objective [31]. Furthermore, since NB-IoT supports multiple carrier

operation, higher IoT capacity can be extended by adding more NB-IoT carriers. For geographic coverage, NB-IoT achieves maximum coupling loss (MCL) of 164 dB, with an extended coverage of 20 dB compared to legacy GPRS devices. With such high MCL, NB-IoT is able to reach out the range up to 35 km.

- **Flexibility**: A need for communication technologies with a high degree of flexibility because the same communication infrastructure must satisfy different applications running on top of it. Flexibility of the smart grid entails the ability to support heterogeneous smart grid services with different data rates and reliability requirements. The flexibility also implies the ability to provide different communication models.
  NB-IoT offers deployment flexibility upon the existing cellular system with three deployment options, as shown in Fig. 1, it can be either plugged into the LTE system or refarming the GSM spectrum. NB-IoT in particular supports a range of data rates, it uses tones or subcarriers each occupied 15 kHz bandwidth rather than the whole resource block. NB-IoT is possible to increase data rates by adding more bandwidth. Data rates could increase by 12 times by allocating devices with multiple tones or subcarriers.
- **Availability**: The availability of the communication structure is based on preferred communication technology. Wireless technologies with constrained bandwidth and reduced installation costs can be seen as a good choice for large-scale smart grid deployments.
  The bandwidth of NB-IoT is substantially narrower (180 kHz) when using in LTE system, whose bandwidth ranges from 1.4 MHz to 20 MHz. Especially for guard-band deployment mode, the spectrum cost of NB-IoT is none. NB-IoT is also a cost-efficient system with less than 5 US dollars per module price and able to support long battery life of more than 10 years with two AA batteries under typical usage patterns. The high availability characteristic of NB-IoT makes large-scale deployment of NB-IoT feasible.

IV. Applications and Communication Requirements

There are many applications for smart grid system that have been developed or are still in the development phase. Different applications usually have different requirements for communication. Hence, the decision on whether NB-IoT can be used for specific smart grid applications should be considered case-by-case.

Based on analysis of previous section, we can see that NB-IoT is a reliable, flexible and cost-effective technology with excellent security, and scalability. It offers low data rate transmission with an insensitive latency. According to the coverage, latency and data rate inherent in NB-IoT, NB-IoT is suitable for NAN applications with less-stringent requirements of latency, such as AMI, demand response management (DRM), electric vehicles (EVs) charging and other customer-based applications. Whereas NB-IoT is unsuitable for those mission-critical NAN applications that require to transmit the significant operation and control information of utilities in real-time, such as distribution automation (DA) and distributed energy resources (DERs). The applications that suitable for NB-IoT, as well as unfit ones, are illustrated as follows.

A. Applications Suitable for NB-IoT

1) AMI: A bi-directional communications network made by the integration of various technologies such as smart meters, advanced sensors, monitoring systems, computer hardware, software, and data management systems to allow the gathering and dissemination of information between user-end and utilities is known as AMI [32]. AMI has the potential to provide remote meter management and outage detection, for instance, it provides utilities with data related to energy consumption for billing purposes, data on power-quality, voltage and load profiles, etc.

The meter reading system needs to support a large number of devices since the measurements are collect from each residential and commercial meter within large scale of coverage [33][34]. According to a report from the national institute of standards and technology (NIST) of the United States, the meter density is 100, 800 and 2000 per km^2 for rural, urban and suburban areas respectively [35]. On the other hand, meter reading system has a very small data rate, for example, a typical meter reading report is 100-200 bytes according to its message format. The requirements of two different types of meter reading services are listed in Table II. i.e., on-demand meter reading (from meters to utility) and scheduled meter interval reading (from meters to AMI head end) [28].

NB-IoT can perfectly satisfy the requirements of AMI applications. It is capable of supporting massive number of low-throughput devices within a wide-range coverage. Huawei and Janz CE has announced and tested the first smart meter based on NB-IoT in November 2016 [36]. This pioneering project has been launched in Lisbon of Portugal in June 2017 with the support of the Portuguese operator NOS, which will become a part of the UPGRID project of the Horizon 2020 Program of the European Commission [37]. However, NB-IoT is not eligible for the real-time metering applications requiring latency as low as 12-20 ms and the high-date-rate applications such as bulk data transmission from all meters.

2) DRM: DRM entails the control of the energy demand and loads during critical peak situations to achieve a balance between electrical energy supply and demand with the objective of improving the reliability and energy efficiency of the power system. The approach most commonly proposed for implementing DRM applications is dynamic pricing, which benefits for both the companies and end-users [38][39]. Pricing applications involve broadcasting of price information to meters and devices. Time-of-use (TOU), real-time pricing (RTP) and critical peak pricing (CPP) programs are typical mechanisms of dynamic pricing. The communication requirements of them are shown in Table II.

The communication requirements of DRM applications depend on their purposes. When the DRM applications are used as a load-balancing tool, there are no special requirements

TABLE II
THE COMMUNICATION REQUIREMENTS OF DIFFERENT APPLICATIONS

Application	Data rate	Latency	Reliability	Security	Coverage	Communication Technologies								
						Wired		Wireless						
						DSL	PLC	ZigBee	WLAN	Z-Wave	Wireless Mesh	WiMAX	LoRa	NB-IoT
Advanced Metering Infrastructure	10-100 kbps per node	5 s - several hours	99.0% - 99.99%	High	5 - 10 km	X	X				X	X	X	X
On-demand meter reading	>100 kbps	<5 s	>99%	High	5 - 10 km	X	X				X	X		X
Multi-interval meter reading	>100 kbps	<4 hours	>99%	High	5 - 10 km	X	X				X	X		X
Demand Response Management	14 - 100 kbps	500 ms-min	>99%	High	5 - 10 km	X	X				X	X	X	X
Pricing-TOU (from utility tometers)	10 - 50 kbps	<1 min	>98%	High	5 - 10 km	X	X				X	X	X	X
Pricing-RTP (from utility to meters)	50 - 100 kbps	<1 min	>98%	High	5 - 10 km	X	X				X	X	X	X
Pricing-CPP (from utility to meters)	10 - 50 kbps	<1 min	>98%	High	5 - 10 km	X	X				X	X	X	X
Grid-to-Vehicle	9.6 - 56 kbps	2 s - 5 min	99.0% - 99.99%	High	10 - 100 km						X	X	X	X
Vehicle to Grid	5 - 10 kbps	<15 sec	99.0% - 99.99%	High	10 - 100 km						X	X	X	X
Distribution Automation	>18 kbps	<1 sec	99.0% - 99.99%	High	Up to 10 km							X		
Distributed Energy Resources	9.6 - 56 kbps	300 ms - 2 s	99.0% - 99.99%	High	10 - 100 km							X	X	

for latency and data rate, which can be exactly satisfied by NB-IoT. The typical data size for DRM applications is 100 bytes, the data latency requirement is usually less than 1 min. Almost 14-100 kbps bandwidth is required per node/device when the applications are used to keep the continuity of remote providing systems and remote turn-off the smart appliances for the peak-shift purpose.

3) Grid-to-vehicle (G2V) and vehicle-to-grid (V2G) charging: EVs are commercially practical due to their significant potential to cut green house gas as well as fossil fuel imports. However, the increasing use of EVs brings in enormous load growth to electric grids, which further aggravates the existing peak power shortage problem. Smart charging system might be the solution to mitigate this problem by switching the information of EV charges and receiving the battery state-of-charge status via the bi-directional communications between EVs and the power grid [40]. The communication requirements of smart charging systems ask for reliability, acceptable response times between 2 s to 5 min, and date rate range from 9.6 to 50 kbps [41].

V2G is a new power-generation paradigm that EVs can be plugged into the electric grid to supply back part of their stored electric power to the power grid for the stability of grid. The communication requirements of V2G depend on the distribution of vehicles. When vehicles are gathered into a fleet such as in parking lots, the short-range wireless communications are applicable. When vehicles are dispersed in a large area, the long-distance communications are preferable. The data rate requirement of V2G is 5-10 kbps and the maximum latency is 15 s.

Due to the mobility of vehicles, only wireless communications can provide solutions for EV applications. The communication requirements of EVs applications can be easily satisfied by LoRa and NB-IoT. Nevertheless, NB-IoT is preferable due to the simplicity of implementation by using the existing cellular infrastructure.

B. Applications Unsuitable for NB-IoT

1) DA: DA systems provide real-time operation information of the grid structure, automation control, data transmission and information management, to automatically and remotely monitor, control, manipulate and coordinate distribution components in power grid [42]. DA systems help utilities to improve the efficiency, reliability, and quality of electric services.

DA provides real-time information such as fault corrections, reducing impacts, and duration of outages, thus the latency requirement is severe in the DA applications. For alarms and alert communications, latency less than 1 s is required. For message transmission between points of some DA functions, latency is required to be 100 ms. And the measured values for power system control signals should not exceed 15 ms [43]. Due to such a stringent requirement on latency, WiMAX and optic fiber techniques instead of NB-IoT are recommended for DA applications.

2) DERs: DERs are small-scale power generation and/or storage devices connected to the distribution grid. DERs is widely recognized as a key enabler of smart grids for its role in smoothing out power fluctuations by complementing renewable generation, such as solar and wind. However, the renewable energy resources are intermittent and unpredictable and non-consistent by nature, thus the responsive, effective communication technologies are required to transmit instantaneous information from different electricity generation points. The bandwidth requirement is around 9.6-56 kbps and the latency requirement is between 300 ms to 2 s [44]. Due to the small latency requirements of DERs, LoRa, WiMAX and fiber optic are suggested to use in DERs applications.

The requirements of applications and their corresponding applicable communication techniques are shown in Table II. ZigBee, Z-Wave and WLAN are suitable for HAN applications due to their limited coverage. Fiber optic is often used in WAN to provide high-data-rate backbone communications. From Table II, we can see that the flexibility of wireless techniques ensures to provide connections for vehicles. Though NB-IoT and wireless mesh techniques share the similar scope of applications, the management and maintaining of NB-IoT can be much simple and economical than mesh network. In Table II, WiMAX is able to satisfy the requirements of most applications, however, the deployment of WiMAX can be costly and the weak diffraction ability makes it difficult to use in urban and hilly areas. In the next section, we will simulate NB-IoT in various scenarios, including urban, rural and hilly areas, to evaluate their performance.

V. Simulations

Due to the mission-critical characteristics of the smart grid, the reliability of NB-IoT should be carefully evaluated before it is employed. BER is the most accurate and direct metric that characterizes the reliability of data transmission over wireless channels. Thus, in this section, we carry out Monte Carlo simulations to analyze the BER performance versus the signal-to-noise ratio (SNR). The channel model is chosen to be COST 207 and some typical communication scenarios of the smart grid, such as rural and urban scenarios, are considered. The simulations are carried out at the link level. All the simulation parameters are selected according to the NB-IoT specifications. The modulation of NB-IoT is selected to be QPSK when deployed in LTE systems and GMSK in GSM systems, respectively. Other simulation parameters are listed in detail in Table III. For fairness, all schemes in our investigation share the same spectral efficiency.

The COST 207 channel models [45] were standardized to enable different communications designers to simulate their systems using a common set of channel models. Four propagation models are defined

- Rural Area (RA): RA usually means a flat area with few hills and tall buildings. RA models are characterized by Rician fading on the first path, and Rayleigh fading on the remaining three paths. The maximum path delay is 0.6 μs. The average K-factor of RA is -1.5 dB.
- Bad Urban (BU): BU usually represents an area which has many dense and high-rise buildings, such as the downtown of the metropolis like Manhattan. BU models are characterized by Rayleigh fading on all paths. The model is constructed by a Rayleigh channel object with 6 taps. The maximum path delay is 6.6 μs.

TABLE III
SYSTEM PARAMETER

Frequency Band	955 MHz
Modulation	QPSK, GMSK
Block length	512
CP length	36
Sample rate	7.68 MHz
Sub-time slots	4
Symbols of time slot	2198
Sub-carrier frequency spacing	15 kHz

- Typical Urban (TU): TU usually represents the ordinary cities with fewer tall buildings or the suburban area of the big cities. TU models are characterized by Rayleigh fading on all five paths, the maximum path delay is 16 μs.
- Hilly Terrain (HT): HT represents an area with the existence of mountains and rolling hills. HT models are characterized by Rayleigh fading on all paths. The channel is constructed with 12 taps. The maximum path delay is 20 μs.

Since most of smart grid applications are lack of mobility, thus the movement speed and Doppler spread in this model are designed to be zero.

In our simulations, the channel estimation is performed based on the preamble, which is located prior to each data symbol and comprises an entire symbol known by both the transmitter and the receiver. Then, the channel estimates are used for the equalization and demodulation of the data symbol. The channel equalization algorithm is zero-forcing. We measure the BER achieved by the maximum likelihood (ML) detector, with channel coding omitted, versus the SNR, which is defined as the ratio of energy per bit and the variance of the AWGN, i.e. E_b/N_0. For simplicity, we assume that the base station, as well as each user terminal, is equipped with a single antenna. Since for in-band and guard-band operation modes, total power is shared between LTE and NB-IoT, performance will be similar. Therefore, in this section we only analyze the performance of in-band operation within LTE systems and that of stand-alone operation in GSM systems.

A. In-band in LTE Systems

Fig. 3 shows the downlink performance of NB-IoT. It can be seen that the performance under COST 207 channel is much worse than that under AWGN channel. This can be easily understood since that the frequency selective fading is introduced in the COST 207 channel model due to the multipath effect. In Fig. 3, we can see that the bit error rate (BER) of RA decreases linearly with E_b/N_0, shows better performance than other scenarios. This happens because the terrain in RA is flat with few hills and tall buildings, thus there is an LOS path exists between the transmitter and the receiver, which provide the dominant component of information. The other three scenarios all experience Rayleigh fading. As the SNR increases, the ICI caused by the delay spread becomes the limiting factor, and thus these three curves exhibit error floors. We can see that the performance of BU performs superior to TU and HT. This happens because there are dense and

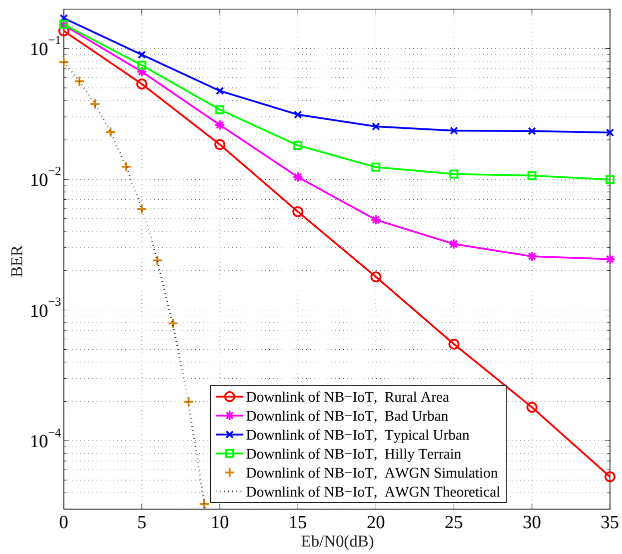

Fig. 3. The BER performance achieved by the downlink of NB-IoT with in-band deployment in different scenarios.

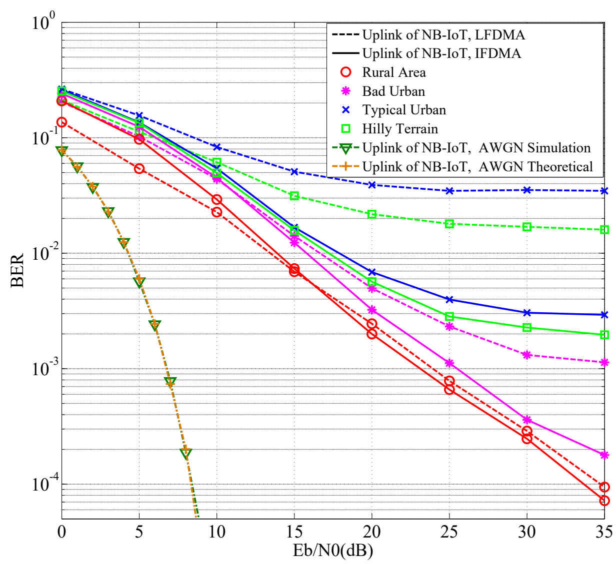

Fig. 4. The BER performance achieved by the uplink of NB-IoT with in-band deployment in different scenarios.

tall buildings in BU, with such high density of obstacles, the maximum path delay of BU is shorter than TU and HT. Thus the coherent bandwidth of BU is bigger than them, making the possibility of deep fading is relatively small than the other scenarios. However, it can be seen that HT performs better than TU even though they have the similar coherent bandwidth. This happens because HT has more diffraction and reflection paths compared to TU with the existence of mountains and rolling hills, thus the more transmission paths brings the diversity gain over independent faded paths.

Fig. 4 shows that the uplink performance of NB-IoT under different scenarios. It can be seen that the curves among different scenarios obey the similar rules as in Fig. 3. For SC-FDMA, there are two ways to map subcarriers, i. e., localized FDMA (LFDMA) and interleaved FDMA (IFDMA). In Fig. 4, we can see that the IFDMA outperforms the LFDMA in almost all the scenarios we tested. This can be explained that with interleaved mapping, the subcarriers within a group are spaced equally in a distance usually greater than the coherence bandwidth, they are likely to experience independent fading statistically. Henceforth, the a frequency diversity gain can be achieved by IFDMA to improve the the system robustness against frequency selective fading.

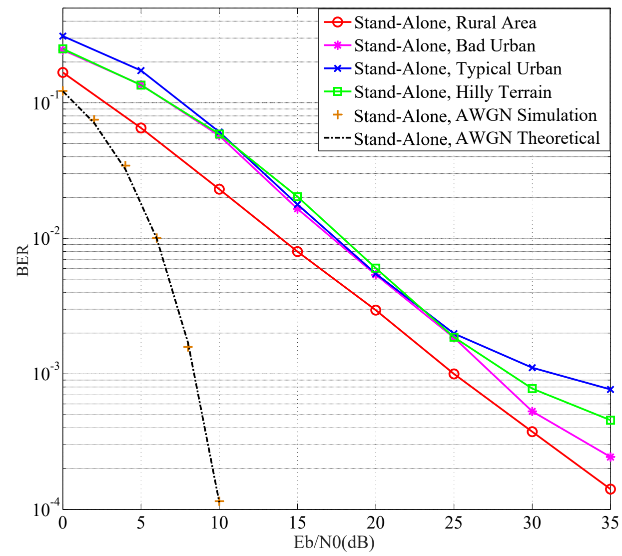

Fig. 5. The BER performance achieved by the NB-IoT with stand-alone deployment in different scenarios.

B. Stand-alone in GSM Systems

Fig. 5 shows the performance of NB-IoT deployed in GSM systems. GSM using Gaussian Minimum Shift Keying (GMSK) as their modulation format. For GSM system, the bandwidth-time product (BT) of the Gaussian filter is 0.3. The theoretical error probability for GMSK is $P_e = Q(\sqrt{2\alpha E_b/N_0})$, as shown in Fig. 5. Where α is a constant related to BT by $\alpha = 0.68$ for GMSK with BT=0.3 and $Q(t)$ is the Q-function. From Fig. 5, it can be seen that the RA performs superior to other scenarios. The performance of BU, TU, HT are close to each other when $E_b/N_0 < 25$ dB. As E_b/N_0 increases, the curves of performance exhibits the similar laws as in Fig. 3-4.

Remarks: Based on the simulations presented above, NB-IoT is demonstrated to work well in all typical communication scenarios in the smart grid. Moreover, due to the widespread coverage of the existing cellular communications infrastructure, NB-IoT is expected to support communications with almost 100% coverage [46]. Therefore, geographically widespread smart grid applications, such as meter reading and DRM, are supposed to be primarily implemented by NB-IoT. As a result, the needs for field trips of personnel for meter reading, manual outage reporting and most restoration operations can be eliminated with the employment of NB-IoT, especially for harsh environments that are difficult for people to access. Numerous performance enhancement techniques that used in OFDM/SC-FDMA can be migrated to NB-IoT due to the similar physical layer design.

VI. Conclusions

In this paper, NB-IoT is proposed for the smart grid to provide secure and reliable communications among different components in the power system. To verify that NB-IoT is the smart choice for the smart grid, we first reviewed available communication technologies, including traditional technologies such as ZigBee and WiMAX as well as LPWAN technologies such as LoRa and NB-IoT. It is shown that the NB-IoT is able to provide communication services that simultaneously achieve long range, appropriate data rate, and high reliability. Then, a comprehensive investigation on the requirements of the smart grid was provided. NB-IoT is scrutinized against each of them, and is demonstrated to perfectly satisfy most of the quantitative and qualitative requirements, such as reliability, security, and scalability. Due to its latency insensitive characteristic, NB-IoT is only suitable for delay-tolerant applications, such as AMI, DRM, G2V, and V2G. Simulations on the performance of NB-IoT in typical smart gird communication scenarios revealed that it is a satisfying technology for smart grid communications. Simulations also demonstrate that it performs better in the presence of LOS paths and the performance can be improved with the subcarrier interleaving technique.

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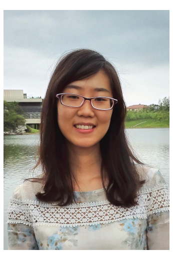

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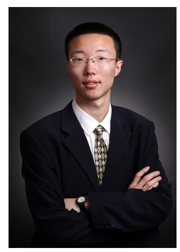

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