Narrowband Internet of Things: Implementations and Applications

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***Abstract*—Recently, narrowband Internet of Things (NB-IoT), one of the most promising low power wide area (LPWA) technologies, has attracted much attention from both academia and industry. It has great potential to meet the huge demand for machine-type communications in the era of IoT. To facilitate research on and application of NB-IoT, in this paper, we design a system that includes NB devices, an IoT cloud platform, an application server, and a user app. The core component of the system is to build a development board that integrates an NB-IoT communication module and a subscriber identification module, a micro-controller unit and power management modules. We also provide a firmware design for NB device wake-up, data sensing, computing and communication, and the IoT cloud configuration for data storage and analysis. We further introduce a framework on how to apply the proposed system to specific applications. The proposed system provides an easy approach to academic research as well as commercial applications.**

***Index Terms*—Communication system, computer networks, Internet of Things, low-power electronics.**

I. Introduction

ADVANCES in micro-electromechanical systems and wireless communications coupled with increasing market demands in human-to-machine/machine-to-machine connections have resulted in the extraordinary popularity and penetration of Internet of Things (IoT) [1]–[5]. It is reported by Forbes that IoT has been playing an important role in a collection of industrial areas, with an excellent performance of being adopted by more than 30% companies in manufacture, retail, and Internet of Vehicle in 2015 [6]. Notably, IoT devices are expected to outnumber 20 billions in 2020, worth 1700 billion U.S. dollars.

The unprecedented flourishing of IoT raises huge demands for machine-type communications (MTC), which can be categorized into threefold: 1) short-distance MTC (distance $\leq$10 m); 2) medium-distance MTC (distance ranges among [10 m, 100 m]); and 3) long-distance MTC (distance $\geq$ 100 m), as shown in Fig. 1. Short-distance MTC has been well investigated and a couple of technologies (e.g., RFID, Bluetooth, UWB, etc.) have been proposed to achieve varying transmission rate requirements. There are also technologies (e.g., WiFi and ZigBee) to meet medium-distance MTC demands. The widely adopted cellular networks (2G/3G/4G) can be good solutions to long-distance high-data-rate MTC. However, long-distance low-rate MTC is a new and ongoing area, and is applicable in scenarios such as meters, tracking, smart parking, smart agriculture, and so on. low power wide area (LPWA) technologies have been introduced as an effective approach in such case.

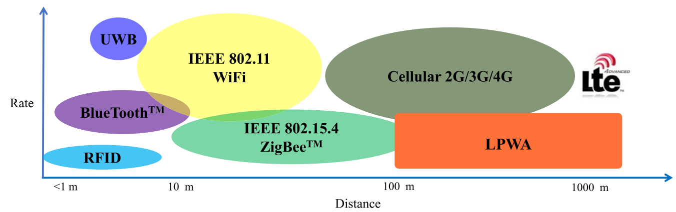

Fig. 1. Coverage and transmission rate comparisons among wireless communication technologies [7].

LPWA technologies are designed to have a transmission distance more than 3 km in complex urban environments and 15 km in open area with strong penetrability [8], [9]. They incur low power consumption such that an ordinary battery can work for years or even more than ten years. Further, LPWA supports narrowband data transmission, with low communication cost. LPWA can either utilize the unlicensed spectrums (e.g., LoRa and SigFox), or 2G/3G/4G cellular licensed resources [e.g., EC-GSM, LTE enhanced MTC, and narrowband-IoT (NB-IoT)]. Among LPWA technologies, NB-IoT proposed by the 3rd Generation Partnership Project (3GPP) standard organization, has been widely recognized as one of the most promising LPWA technologies [10]–[12]. It stemmed from the NB M2M study item application proposed by Huawei Corporation in 2014 and was frozen at Release 13 of the 3GPP specification in 2016.

Clearly, NB-IoT is still in its infancy. There are many theoretical as well as practical issues needed to be addressed. To boost its development, using the newly available integrate circuit (IC) made by Huawei Hisilicon Technologies

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TABLE I
COMPARISONS AMONG LoRa, SigFox, eMTC, AND NB-IoT

Parameters/Technologies	LoRa	SigFox	eMTC	NB-IoT
Spectrum	unlicensed	unlicensed	licensed	licensed
Modulation	CSS	UL:DBPSK DL:GFSK	UL:SC-FDMA DL:OFDMA	UL:SC-FDMA DL:OFDMA
Bandwidth	7.8 kHz-500 kHz	200 kHz	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (1200 kHz carrier bandwidth)
Range	urban:2∼5 km suburban:∼ 15 km	urban:3∼10 km suburban:30∼50 km	urban:∼ 5 km suburban:∼ 17 km	urban:1∼8 km suburban:∼ 25 km
Data rate	<50 bps	<100 bps(EU) <600 bps(USA)	<1 Mbps	160∼250 kbps(DL) 160∼200 kbps(UL)
Battery Life	>10 years	8∼10 years	5∼10 years	>10 years
Price	<$5	∼ $10	<$10	<$5

Company Ltd. or Qualcomm Inc., several vendors such as Quectel, designed communication modules for NB-IoT. However, it is difficult and inconvenient to conduct research on NB-IoT or extend its applications by utilizing only the modules. In this paper, after demonstrating the advantages of NB-IoT by comparing it with other LPWA technologies, we design a prototype system including NB-IoT devices, IoT cloud platform, application server, and user app. We also provide a framework on how to apply NB-IoT to specific applications. Such a prototype system provides an off-the-shelf way for academic research as well as commercial applications.

The remainder of this paper is organized as follows. We introduce a collection of LPWA technologies in Section II. We present the proposed system in Section III. We discuss the implementation and application of NB-IoT in Section IV. We conclude this paper in Section V.

II. OVERVIEW OF LPWA TECHNOLOGIES

Many LPWA technologies have been proposed recently for a variety of applications. LoRa, SigFox, enhanced MTC (eMTC), and NB-IoT are among the most popular ones [13]. We briefly introduce them in this section, providing a comprehensive comparison (refer to Table I).

LoRa, designed by Semtech Company, is built on proprietary spread spectrum techniques and Gaussian frequency shift keying (GFSK). It is known as the first low-cost wide-area implementation for commercial usage. LoRa utilizes chirp spread spectrum (CSS) as well as GFSK modulation to prevent in/out-band interference, and can work up to 25 dB below the noise. The bandwidth required by LoRa can be flexible, varying from 7.8 to 500 kHz. The expected coverage range in urban is 2∼5 km and about 15 km in suburban.

SigFox also utilizes unlicensed spectrum (i.e., industrial, scientific, and medical radio band) by adopting a proprietary technology. The frequency it uses in Europe is 868 MHz and 915 MHz in U.S., respectively. SigFox provides mono and bi-directional communication, employing DBPSK/GFSK modulations for uplink/downlink transmissions. As an operated wide area network, it provides connectivity without deploying specific network infrastructures for each application. The demanding bandwidth is 200 kHz, with a data rate less than 100 kb/s in Europe and 600 kb/s in U.S.

LTE eMTC is a new type of data communications which involves one or more entities without human interaction. eMTC is standardized by 3GPP and operated on the LTE resources. 3GPP provides services between eMTC application in user equipment and that in an external network. eMTC is featured by relative large data transmissions (≤1 Mb/s), low mobility, large coverage range (5 km in urban and 17 km in suburban), etc.

NB-IoT is a new 3GPP radio access technology, designed to achieve excellent performance with legacy GSM and LTE technologies. It requires 180 kHz minimum system bandwidth for both downlink and uplink communications, and can be deployed under three operation modes: 1) stand-alone; 2) guard-band; and 3) in-band. The downlink transmission scheme is based on orthogonal frequency division multiple access (OFDMA) with 15 kHz subcarrier spacing for these three operation modes. NB-IoT physical channels and signals are time multiplexing. Typically, NB-IoT supports uplink transmission with a data rate around 160–200 kHz and downlink transmission at a data rate around 160–250 kHz. It can cover areas in urban and suburban environments of ranges 1–8 km and 25 km, respectively. As can be seen in Table I, NB-IoT has a low manufacture cost, long operation life and wide coverage, compared with other three LPWA technologies. It has wide applications in a variety of fields.

III. SYSTEM DESIGN AND IMPLEMENTATION

In the section, we design a system which includes NB-IoT devices, cloud platform, application server, and user app, as illustrated in Fig. 2. By using the proposed system, users only need to purchase and install an NB-IoT SIM card into the development board in order to enable NB-IoT communications.

Specifically, in the designed system, sensing and communication modules are integrated into an NB device. The sensing data are collected and transmitted to an IoT cloud platform, which then pushes the received data to the application server built for each application. The IoT platform can be either a commercial platform, such as Huawei cloud platform or China Mobile OneNet, or designed, built, and maintained by end users. In our design, we use the Huawei cloud platform named OceanConnect. The user app is used to connect users and application server, or request real-time data from NB devices via cloud platform. Since it is easy to develop the user app and application server (many companies provide such a tailored development service), we focus on the technical part

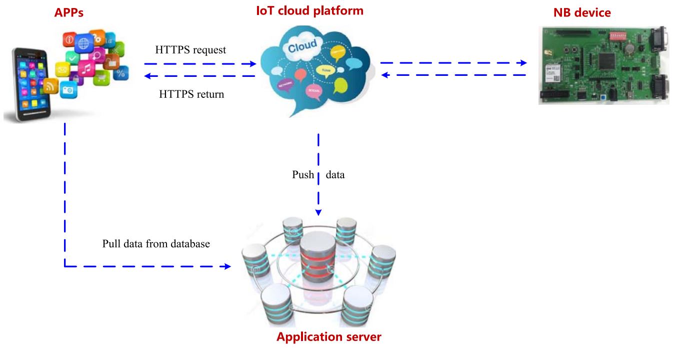

Fig. 2. System design.

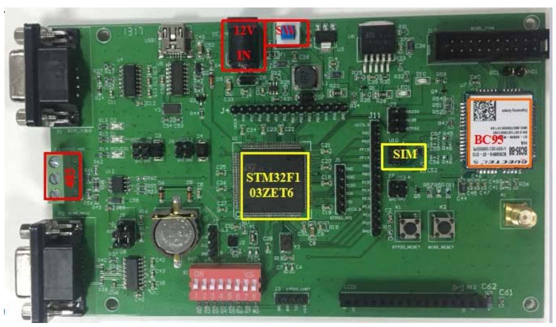

Fig. 3. Designed development board.

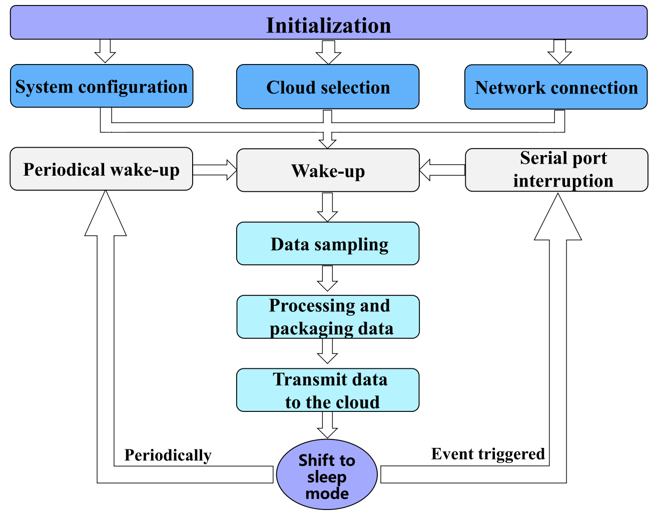

Fig. 4. Firmware design.

of the system, that is, the design of development board for NB devices, firmware design and implementation to enable data sensing, computing and communication, cloud service configuration.

A. Development Board

The NB-IoT communication module, integrated with a SIM card, can realize long-distance low-power communications, however, it does not provide any ports to connect sensors. Further, it lacks computing capability. Thereby, we design a development board for the module BC95-B8 to inhabit. The designed hardware suite can be off-the-shelf for varying purposes, reducing the development costs and accelerating the development-to-market time.

The basic development board is mainly composed of sensors, a micro-controller unit (MCU), an NB-IoT module, a power management, and a number of functional peripherals. It can achieve multiple functions such as data sensing, data processing, data communication, data display, etc. The MCU is centered at the suite, which contains liquid crystal display interface, universal serial bus to universal asynchronous receiver/transmitter interface, recommended standard 485 interface, user input/output pin, analog-to-digital converter (ADC) interface, serial port, serial peripheral interface (SPI), inter-IC (IIC) interface, joint test action group (JTAG) port and download port, and it connects with the dial switch and sensors. The NB-IoT module is connected to the SIM card, serial port, JTAG download port and antenna. The SIM card, the NB-IoT module and the antenna are core components to enable NB-IoT communications. Power management module provides a variety of power supplies for the entire development board.

The development board we design is shown in Fig. 3. We select STM32 as a controller, as this series of single-chip microcontroller have been widely used in low-cost embedded systems. An appropriate type can be decided according to application requirements. The NB-IoT module we select is BC95-B8 of Quectel, with 900 MHz frequency band. The power management chips (MP2359, AMS1117, MIC29302WU) are adopted for voltage conversion, which can provide 5 V, 3.3 V, and 3.8 V voltage, respectively.

Specifically, antenna design is important for transmitting or receiving signals. The impedance used in the antenna is crucial. The impedance should not be too large or too small, or it may weaken signals strength. We test different impedances to find the optimal one (around 40 Ω) at which strongest signals can be obtained through simulations. The advantage of our design is that the development board has numerous interfaces for different applications. Different modules can be connected to the development board, which is convenient for the future developments.

B. Firmware Design

System firmware is a core component of the NB-IoT system, specifying how to activate sensors, sample and process data, and transmit them to the IoT cloud platform. We have designed a firmware and implemented it on NB devices using the integrated development environment provided by Code Composer Studio of Texas Instruments, which includes a set of tools for developing and debugging embedded systems.

A schematic of the designed system firmware is depicted in Fig. 4. There are mainly three phases for the components in the firmware to work. At the initialization phase, system configuration is conducted. Then, a host cellular base station and a destination cloud are associated with the NB device. At the operation phase, the NB device reads sensing data from sensors, processes and packages them, and sends them to the communication module. Finally, the NB device turns to sleep mode. In the system firmware design, it comprises of three main functions: 1) hardware drivers; 2) communication management; and 3) low-power management.

A hardware driver functions as the interface of the system docking hardware, sending commands of data sampling/sleep to sensors. Depending on specific applications, an interface function needs to be provided for each type of sensors, which may increase the development cost. Fortunately, most of sensor interfaces can be divided into several common parts such as serial port, SPI, IIC, ADC, etc. For example, the temperature sensor usually complies with ADC interface or IIC interface. Therefore, driver codes can be reused for different applications. After the controller finishes the configuration, the hardware driver then interfaces with sensors and collects data accordingly.

After the system obtains the sensing data through hardware driver and processes it in accordance with the application's request, it is still required to package the processed data to conform with the communication protocol. NB-IoT communication module provides a way of default for data packaging: the constrained application protocol. Data packaged in this way will be transmitted to the cloud platform provided by Huawei Corporation. Alternatively, sensing data can be packaged by the controller of the integrated software development kit, specified by applications. In such a way, sensing data can be transmitted to the cloud platform built by applications.

We also design a low-power management to minimize the overall power consumption. NB-IoT supports two new technical low-power modes, namely power saving mode (PSM) and extended discontinuous reception. In our design, we use the PSM as the main power-saving mechanism, i.e., NB devices will enter sleep mode in which it cannot be waken up by nearby base stations. Hence, nearby base stations are not able to initialize communications to NB devices in PSM mode. An NB device can only be activated by the internal interrupt of an NB device. Two kinds of interrupt are employed: one is the timer interrupt, i.e., the PSM time is counted by a real time clock; the other is the interrupt from sensors when their collected data is out of a predefined region. Clearly, an NB device is in PSM or sleep mode most of time, leading to significant power saving.

C. Cloud Service Configuration

Cloud-based IoT systems have great significance on smart cities or homes [14], [15]. In NB-IoT, cloud platform stores sensing data from NB devices, performs data analysis and forwards command messages from users (apps) to NB-IoT devices.

To enable the interaction between NB devices and the cloud platform, north registration and south bounding are needed. In north registration, all NB devices for a specific application have to be registered on the cloud platform. This requires users to send an http/https request containing International Mobile Equipment Identity (IMEI) number of devices and other application-related information to the cloud platform. South bounding is to link devices to the corresponding storage zones in the cloud platform. This occurs when a device sends

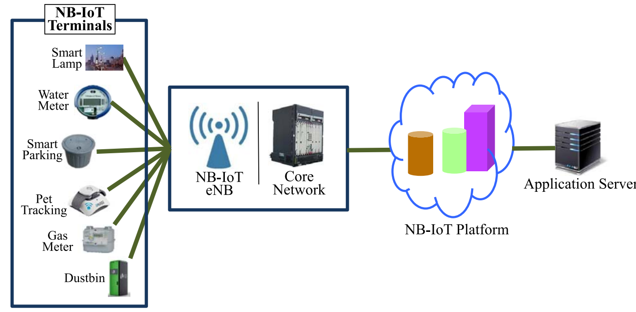

Fig. 5. NB-IoT application architecture.

data to the cloud platform for the first time. The data uploaded to the cloud platform include sensing data and device IMEI number. The cloud platform accepts the data only when the device IMEI number matches a registered one. For security reasons, the uploaded data is encoded before transmission and decoded after being received at cloud platform.

When a user needs to retrieve data collected by NB devices, he/she can send query request to the cloud platform, which, after authentication, will return the requested data from the database. Alternatively, the user can send the query request directly to the application server, which is built by the application instead of the NB service provider. To achieve this, whenever the cloud platform receives data from an NB device, it will push the received data automatically to the application server. In such a way, we can have a synchronized local database, resulting in more efficient data query and analysis.

When a user needs to send a command message to an NB device, e.g., we may need to change the setting of an electricity meter remotely, he/she first sends an http/https request containing the command to the cloud platform, which then forward the command message to the corresponding NB-IoT device. After receiving the command message, the device will execute the command and return the results (or execution state) back to the cloud platform. The returned message will be stored in the cloud and pushed to the application server as stated in the previous paragraph. For security reasons, messages are all encoded during transmission.

IV. Application Architecture

NB-IoT has been reported to find applicability in not only traditional businesses (e.g., wireless sensor networks [16], [17], smart metering and tracking [18]), but also in many emerging industries such as smart city [19] and eHealth [20]. In this section, we proceed to provide a framework for NB-IoT applications based on the system we have designed.

An application architecture is shown in Fig. 5. The framework is composed of four components: 1) NB-IoT terminals; 2) data receiving and transmission networks; 3) NB-IoT cloud platform; and 4) application server. Various NB-IoT terminals (e.g., smart lamp, water/gas meter, dustbin, etc.) are connected to a set of NB devices, which will transmit application-dependent sensing data to cellular base stations. The data then are relayed to the NB-IoT cloud platform, which will forward the data to specific application servers. Clearly, it will greatly reduce the development cost for an application by adopting the proposed system in this paper.

Take smart metering for an example. In such an application, the consumption of electricity, water, gas, etc. should be collected periodically to determine the payment of users. It has the following basic requirements, including: 1) massive meters with low cost; 2) low power consummation with long-term battery lifetime; and 3) improved indoor coverage. Our designed system as instructed above can meet these requirements quite well. It enables different charging policy based on information collected in different time of a day.

The various services and applications supported by NB-IoT can be classified into four categories, i.e., IoT Appliance, Personal, Public, and Industry [9]. With NB-IoT in appliance, management, and control [21] are more efficient through the improvements in big data analysis. The applications for IoT Personal create a personal area network. Examples include wearables, smart bicycle, pet tracking, etc. For IoT Public, as the name suggests, it focuses on the applications which serves the general public, including smart metering, smart garbage bins, etc. For IoT Industry, NB-IoT can improve the efficiency of enterprise and industry. The corresponding applications include logistics tracking, asset tracking, smart agriculture, etc. With the system we have developed in this paper, it becomes quite promising to realize these applications.

V. Conclusion

In this paper, we designed a tailored system that can promote the popularity of NB-IoT. The system consists of four core components: 1) NB devices; 2) cloud platform; 3) application server; and 4) user app. We implemented the system by providing hardware as well as firmware design and cloud service configuration. We showed how to apply the proposed system to varying scenarios, in which the development cost can be significantly reduced.

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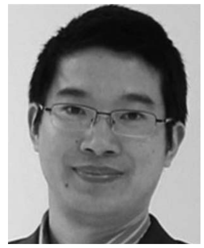

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