Connecting Intelligent Things in Smart Hospitals Using NB-IoT

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***Abstract*—The widespread use of Internet of Things (IoT), especially smart wearables, will play an important role in improving the quality of medical care, bringing convenience for patients and improving the management level of hospitals. However, due to the limitation of communication protocols, there exists non unified architecture that can connect all intelligent things in smart hospitals, which is made possible by the emergence of the Narrowband IoT (NB-IoT). In light of this, we propose an architecture to connect intelligent things in smart hospitals based on NB-IoT, and introduce edge computing to deal with the requirement of latency in medical process. As a case study, we develop an infusion monitoring system to monitor the real-time drop rate and the volume of remaining drug during the intravenous infusion. Finally, we discuss the challenges and future directions for building a smart hospital by connecting intelligent things.**

***Index Terms*—Internet of Things (IoT), Narrowband IoT (NB-IoT), smart hospital.**

I. Introduction

With the rapid development of mobile Internet, Internet of Things (IoT), and wearable devices, the health monitoring has shown an intelligent trend in recent years. Many hospitals have already made use of mobile phone apps for appointment registration, inquiring electronic medical records, and examination results. In addition, medical wearable devices [such as 3G blood pressure meter, Bluetooth blood glucose meter, and smart electrocardiograph (ECG) device] have been used to monitor blood pressure, blood sugar, ECG and other physiological signs. The monitoring records are finally sent to the information platform for real time diagnosis or to a medical database for record keeping [1].

The introduction of intelligent devices to hospitals can save the operation cost, enhance the medical experience of patients and reduce the labor intensity of medical staff [2]. However, connecting those intelligent things to achieve such goals is still a great challenge. The main limitation is the communication protocol [3]. The wired communication is not suitable for mobile devices. Many researchers have tried to build an architecture for connecting intelligent things by short range and long range wireless communications. Boudra *et al.* [4] introduced a monitoring system for patients using ZigBee and a long range wireless protocol. Catarinucci *et al.* [5] proposed a three-tier network architecture for monitoring and tracking of patients and environmental data in hospitals, which contains three parts: 1) the radio frequency identification (RFID) enhanced wireless sensor network called hybrid sensing network (HSN); 2) the IoT smart gateway; and 3) user interfaces for data visualization and management. The HSN tracked sensor devices with RFID Gen2 tags and forward their data to the Internet or local area network by the middle layer. Alharbe *et al.* [6] proposed a way of using ZigBee and RFID to build an information management system of hospitals. In this system, ZigBee was used to transmit the collected information to the cloud center, and RFID was used to identify objects automatically. Nasri and Mtibaa [7] proposed an idea of transmitting data from terminals to smart phones using 5G communication techniques, which were finally sent to the cloud center for the further treatment. Zhanwei and Yongjian [8] put some smart devices on patients to upload data to the cloud platform. However, the existing architecture cannot connect all types of devices in hospitals due to the limitation of wireless protocols. Short range wireless protocols like Wi-Fi, ZigBee are limited by the communication distance. Long range wireless protocols usually have high energy consumptions which are not suitable for smart devices in hospitals [9].

Narrowband IoT (NB-IoT) is a low power wide area wireless protocol that works virtually anywhere [10]. NB-IoT has the advantages of low cost and low power consumption [11], [12], which provides a new way for connecting devices that require small amounts of data, over long periods, in hard to reach places and has been used in intelligent parking, intelligent meter reading and the ofo shared bicycle. The emergence of NB-IoT makes it possible to formalize an architecture to connect all intelligent things in smart hospitals. One of our motivations is to formalize an architecture using NB-IoT to connect all intelligent things in smart hospitals. As a case study, we select the infusion monitoring issue which troubles patients deeply especially those patients who are given fluids in the evenings. We first design an infusion monitoring terminal using infrared sensors and then connect those devices with NB-IoT.

Intravenous infusion is a common treatment for its rapid drug use and small trauma. However, medical staff cannot monitor the infusion constantly, which makes the drop rate

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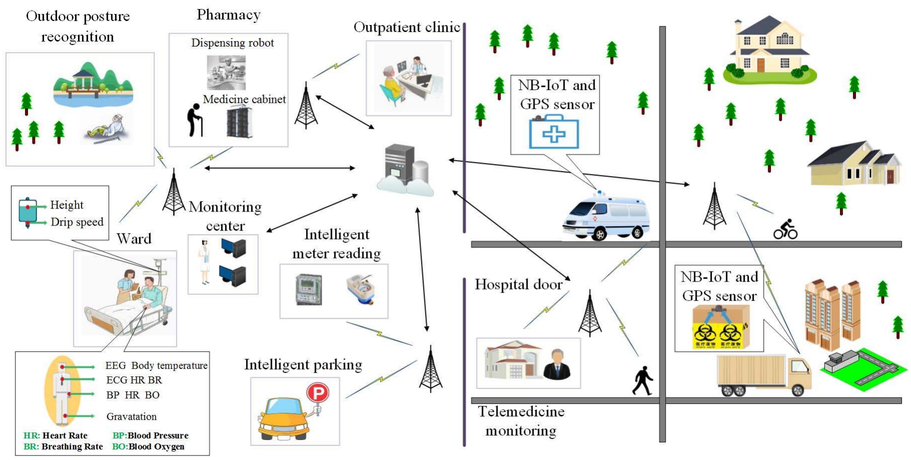

Fig. 1. Illustration of the application scenarios for smart hospital.

anomaly and drug replacement unable to be timely noticed. The development of real-time infusion monitoring devices has great significance for both medical staff and patients.

There exist three types of monitoring techniques, respectively, using the gravity sensor, capacitor, and infrared sensor. Chen *et al.* [13] designed a device using the gravity sensor, which can obtain the drop rate and remaining drug volume by the monitored gravity of drug bottle. There are two main problems with this device. One is that it cannot calculate the drop rate accurately because the external influences cannot be ignored for the high precision gravity sensor on a 0.05 g level. The other is that it cannot calculate the remaining drug volume accurately because it cannot accurately remove the tare of the infusion bottle and device. Ogawa *et al.* [14] developed an electrode-based infusion monitoring device. However, it was unapplicable because of the higher requirements of the influence of drug to the value of the capacitor, the material of the infusion device and the length of the droplet dripping. Wang *et al.* [15] and Chen *et al.* [16] introduced the device using the infrared photoelectric sensor. However, they did not consider the interference of the natural light on the photoelectric equipment. They did not yet give process to calculate the remaining drug volume by the amount of drops.

The infusion monitoring device based on the infrared sensor is low in power consumption, low in cost, easy to use, and accurate in the drop rate measurement. Another motivation of this paper is to design an infusion monitoring device based on the infrared sensor to overcome the existing defects and connect them by NB-IoT. The main contributions of this paper are summarized as follows.

- We formalize an architecture based on NB-IoT to connect all intelligent things in smart hospitals, which takes the advantages of the higher capacity, wider coverage, lower power consumption, and lower cost of NB-IoT. However, using NB-IoT for medical applications, the latency is the main challenge for those devices with high real-time requirements like ECG [17]. To this challenge, we introduce the edge computing to the proposed architecture.
- As a case study, we design an infusion monitoring device based on the infrared sensor and NB-IoT. We use the infrared signal modulation scheme to deal with the light interference, which enables our monitoring device to count the drops accurately in the sunlight. Then we formalize a fault detection process and a learning algorithm for the drop coefficient to calculate the remaining drug volume accurately.
- We give the challenges and future directions for building smart hospitals to connect intelligent things based on the proposed architecture.

The rest of this paper is organized as follows. Section II introduces application scenarios in smart hospitals. In Section III, we propose an architecture to connect all intelligent things. Section IV develops an infusion monitoring system using NB-IoT as a case study. In Section V, we present some challenges and future directions. Finally, Section VI concludes this paper.

II. Applications Scenarios and Characteristics

Fig. 1 depicts the typical application scenarios in smart hospitals by connecting intelligent things. Various sensors located inside or outside the hospital collect data including the physiological sign data like heart rate and blood pressure, environmental data like temperature, and other data like parking space data. These data are finally sent to the cloud platform through the wireless communication for decision-making and analysis.

A. Application Scenarios

1) Intelligent Parking: Parking spaces in hospitals can be controlled by smart locks. A patient can reserve a parking space using a mobile app before he goes to the hospital. The reserved parking space will be locked until the patient arrives and sends it an unlock order by wireless communication. When the patient leaves the hospital, the parking space can be auto-locked and the settlement of cost can be automatically completed.

2) Access Control: Some important departments of hospitals need to install access control systems. When a staff approaches a building door, commands can be sent to the

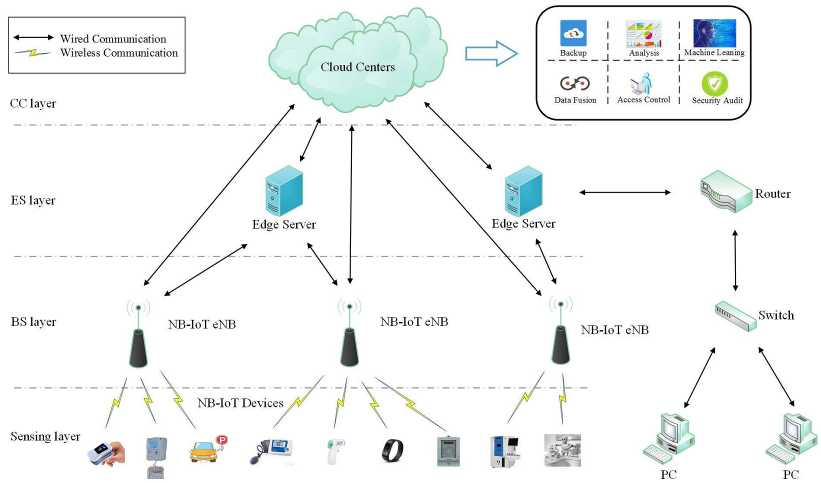

Fig. 2. Proposed architecture for connecting intelligent terminals in smart hospitals.

system using wearable devices to complete the authentication. If the authentication is successful, the door will open. Some staff can also carry out remote unlocking if necessary.

3) Ward Care: In the ward, the patient's real-time physiological sign like heart rate or the environmental information like the cleanliness can be collected by wearable devices or smart sensors. These data are then transmitted to the monitoring center by wireless communication. If the patient's physiological sign is abnormal, the paramedics can make the corresponding treatment in time.

4) Outpatient Medical Treatment: Outpatient doctors can get a comprehensive understanding of the patient's health based on physiological sign data collected by wearable devices, which can assist doctors to make accurate diagnosis, improve the efficiency of doctor's diagnosis, and save the patient's time.

5) Outdoor Posture Recognition: When the patient is outdoors, the patient's body and motion posture can be identified by posture sensors to identify whether a dangerous pose has occurred, which can also determine whether the abnormal physiological sign is a false alarm for normal situation [18].

6) Telemedicine Monitoring: Some of the discharged patients need to be monitored at home. Wearable devices can monitor the patient's physiological sign remotely [4], [19]. When the patient's physical condition is abnormal, the device can notify the patient's family or the attending doctor in time to prevent accidental occurrence.

7) Other Applications: We can realize intelligent meter reading by adding wireless communication module to the traditional electricity and water meters in the hospital. Some expensive medical equipment like gamma rays can be connected to the IoT system, then the equipment checking can be regularly completed. When some valuable medical item or medical waste is removal, the installed sensors can deliver the real-time location and status data to the cloud platform for effective monitoring [20].

B. Characteristics of Medical IoT Devices

In the medical IoT, there are a large number of sensors used to monitor patients, the environment of hospitals, and the conditions of medical devices. The number and type of these sensors are particularly large. In addition, most devices use battery power, the capacity of which is limited due to the limitations of size and other aspects. Medical IoT devices have the characteristics of low power consumption to ensure them work for a long time because they cannot replace the battery or charge regularly [21].

III. NB-IoT-Based Network Architecture for Smart Hospitals

A. Challenge of NB-IoT for Medical Applications

Although NB-IoT has many unique and excellent properties, it has yet the disadvantages of high latency and poor mobility. NB-IoT standard is set mainly for non mobility, latency-insensitive, loading of multidevice, and low power consumption scenarios. The protocol itself removes the reporting process of the terminal measurement report commonly used in traditional mobile communications, which although saves the power consumption of the terminal device, but also removes the handoff function of data communication. In addition, the protocol is designed for the network architecture with many access devices and low power consumption requiring. To prevent the data transmission congestion caused by a large amount of devices in a centralized manner and reduce the power consumption of devices, NB-IoT does not make strict control over the communication latency. This may be a challenge in some application scenarios of smart hospitals, e.g., in the intensive care unit, some physiological sign data of patients with severe diseases need for real-time uploading, which requires a low latency.

B. Proposed Architecture for Smart Hospitals

There are several advantages of using NB-IoT in smart hospitals.

1) *Higher Capacity:* NB-IoT can provide billions of connections and connect tens of thousands of users in a single neighborhood, which can meet the connection requirements of equipment in smart hospitals.

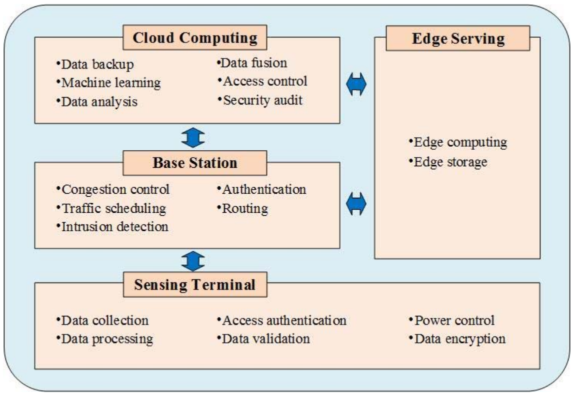

Fig. 3. Main function and mechanism considered for each layer in the proposed architecture.

2) *Wider Coverage:* Comparing with the existing mobile network, NB-IoT increases a 20db+ link budget, which significantly enhances its penetration ability and enables it to be very suitable for the equipment connection of hospitals' buildings and basements.
3) The lower power consumption with a battery life over ten years, which is very suitable for the devices like wearable devices which have small sizes.
4) *Lower Cost:* The cost of each module is less than 5 $, which can significantly reduce the cost of disposable equipment.

Fig. 2 gives an architecture of smart hospitals based on NB-IoT. In this architecture, the terminal devices in the sensing layer collect and send data to the base station (BS). To the requirements of low latency and real-time processing, we introduce edge serving which provides data interface for both BS and the cloud platform. In the cloud computing layer, the cloud platform stores and processes global data which have no high demand for latency, and controls the overall situation with big data analysis and machine learning. The function and design requirements for each layer in the architecture are shown in Fig. 3.

1) Sensing Layer: In the sensing layer, there are a large number of terminal devices integrated with NB-IoT modules. These devices have the functions of data collection and processing. In addition, the scheme of energy consumption and security should also be considered to deal with the energy supply and security of terminal devices.

In smart hospitals, we need to collect many kinds of data. For example, we can use the photoelectric sensors to collect data, such as heart rate, blood pressure, and oxygen saturation, use 3-D acceleration sensor to acquire the posture of patients. Most of terminal devices use fixed battery to provide power and require long time work without interruption, to which the control of power consumption is very important. We should use CPU with low power consumption, and design reasonable dormancy mechanism to set the sensor into dormant state as much as possible after the predetermined work, and utilize data fusion and other operations to reduce data traffic, which can reduce the working time of communication module. In addition, we should consider the energy conversion and wireless charging techniques to make a convenient energy supplement to ensure devices for a long working time.

Due to the limitation of resource, the terminal devices are vulnerable to be attacked. For data privacy and security, the sensing layer requires security mechanisms like access authentication, data encryption, and data check. Access authentication requires two-side authentication between devices and the BS. It can effectively avoid the devices from accessing to pseudo BS. Using the data check mechanism, we can deal with packet loss and packet error in the wireless transmission process to ensure the integrity of data transmission. Due to the limited computing ability of the terminal sensor, a lightweight data encryption algorithm should be adopted to ensure the confidentiality of data.

2) Base Station Layer: In the BS layer, a large number of NB-IoT BSs are deployed, which need mechanisms of routing, congestion control, traffic scheduling, and security to ensure the integrate and secure transmission of data.

When the BS obtains the data from the sensing layer, it need to plan a reasonable transmission path by the data requirement. For example, the BS directly sends the data which require low latency to the edge server for storage and computing. In smart hospitals, a large number of terminal devices are accessed. They send a large amount of data which may lead to the congestion and data loss. This requires mechanisms of congestion control and priority ensuring the transition of data with high priority to avoid the failing of monitoring of patients or equipment due to the occurrence of network congestion. In addition, it also need to schedule the traffic of the BS when congestion occurs.

Identity authentication and intrusion detection can be used to guarantee data security in the BS layer. The authentication is a process that reviews the user's identity and determines whether the user has the permission to access. In addition, the BS is also vulnerable to be hacked, so we need an intrusion detection mechanism, which can collect and analyze network behaviors, security logs, audit data, and other key information to check whether there are violations to the security policy. Intrusion detection can intercept intrusions to effectively prevent the BS layer from being destroyed.

3) Edge Computing Layer: The traditional computing and storage of big data are carried out in the cloud platform. This centralized data processing will expose its inherent problems in the medical IoT architecture, because it connects a large number of devices generating data with a massive level and the linear growth of cloud computing ability cannot match the explosion of marginal data. In addition, each NB-IoT BS can connect up to 50 000 devices, which increases the load of the transmission bandwidth and network latency. On the other hand, some data in smart hospitals have high requirements for latency, so we introduce the edge computing server in the architecture to reduce the latency and accomplish the real-time data processing.

There are several benefits of introducing edge computing [22] to the proposed architecture.

1) The edge server is relatively close to the terminals, the round trip time of data is relatively short which greatly reduces the latency. This can greatly benefit the

monitoring with the high requirement of latency like the monitoring in intensive care.

2) The edge server can increase the reliability of the systems. Without edge servers, the data collected by terminals must be transmitted to the cloud platform, which may pass a variety of servers, routers, and other network equipment. In addition, considering network attacks and other factors, data reliability cannot be effectively guaranteed. Using edge servers, the terminals can directly access data on the edge servers without forwarding by other devices and networks, which greatly ensures the reliability of the data.
3) The edge server can reduce the energy consumption of terminal devices. The edge server has the powerful calculation capability and it is close to the terminals with a low latency, so we can put the computing tasks of the terminals to the edge server. Then the terminal device need only to upload data and download the result from the edge server, which can greatly reduce the computational cost of the terminals and significantly reduce its power consumptions.
4) A large number of applications can be deployed in edge servers which can provide a flexible service environment.

4) Cloud Computing Layer: In the cloud computing layer, the cloud center uses big data analysis, machine learning, and data fusion techniques to conduct comprehensive data processing of the entire system. In addition, access control, security audit, and data backup are also introduced to ensure the data security.

The cloud center can use big data technique to process its own data or data retrieved from the edge computing server, use the data fusion technique to correlate and synthesize different kinds of data and information, and utilize machine learning algorithms like random forest algorithm, Bayesian network, neural network, hidden Markov model to extract knowledge and rules from historical data to carry out intelligent diagnosis, and auxiliary decision-making.

Cloud security is also an important problem confronted by the cloud center. Access control is the most important problem of security. Security audit is also an important technique to ensure the security of cloud center, which can make use of information, such as records, system activities, and user activities to test the environment and activities of operating events to discover system vulnerabilities and intrusions.

IV. Injection Monitoring System: Case Study

Due to the advantages like low cost and accurate measurement, the monitoring device based on the infrared sensor will become the trend for injection monitoring. As a case study, we propose a design of injection monitoring devices using the infrared sensor and connect them with NB-IoT to form an injection monitoring system.

A. Challenges of Injection Monitoring With Infrared Sensors

Using infrared sensors to monitor the droplet, the monitoring device must be fixed on the Fimos drip pot of the infusion device, which strictly limit the size of the monitoring device. The first challenge of the monitoring device is the energy consumption, as the battery capacity will be limited by the size of the device. We must reduce the power consumption as much as possible for the device's long time work without interruption. The second challenge of the monitoring device using infrared sensors is the light interference. When the light shines on the device, the receiver can still receive the infrared signal during a droplet drips from the top of the Fimos pot. The last challenge is the fault repairing and the calculation of the remaining drug volume. Due to the resource limitation and environmental factors, the faulty drop counting is inevitable. In addition, the monitoring device can count the total number of drops, but it must be converted to milliliter for calculating the remaining drug volume which relies on the drop coefficient of the infusion device. However, different infusion devices have different drop coefficients, which makes the calculation of the remaining drug volume difficult.

B. General Design of the Injection Monitoring System

Our monitoring system includes three parts: 1) the monitoring terminal; 2) the initialization unit; and 3) the monitoring platform. The monitoring terminal counts the real-time droplets during the infusion process using the infrared sensor, and sends the number of drops to the monitoring platform per 20 s by NB-IoT. After receiving the data from the monitoring terminal, the monitoring platform first detects and repairs faults and then converts the total number of drops to milliliter using a learning algorithm which is used to obtain the accurate drop coefficient of the infusion device and calculate the remaining drug volume.

The main purpose of the initialization unit is to bind the monitoring terminal to a bed number. Before the monitoring terminal is used, we put it on the initialization unit to read the bed number written in the E^2PROM of the initialization unit by four copper pillars. Then the monitoring terminal sends its identification and the corresponding bed number to the monitoring platform and completes the binding process.

C. Detailed Design of the Injection Monitoring System

The monitoring terminal is used to collect the drop information, and send the collected data to the monitoring platform. In addition, we consider the mechanisms of energy saving, safety check, and encryption for the data security in the design of the monitoring terminal.

1) Monitoring Terminal: The main problem for infusion monitoring using infrared sensors is the interference of light shining. The light contains the infrared band (940 nm) transmitted by the sensor, which can result in signal flooding, irregular clutter, or other circumstances. In the design of the monitoring terminal, we modulate the infrared signal from the transmitting terminal into a specific frequency square wave (38 kHz), and make the receiver to demodulate only the corresponding frequency signal, which successfully realizes the filtering of the irrelevant interference signal.

Fig. 4 shows the block diagram of the droplet counting module. The module contains an infrared emission tube and

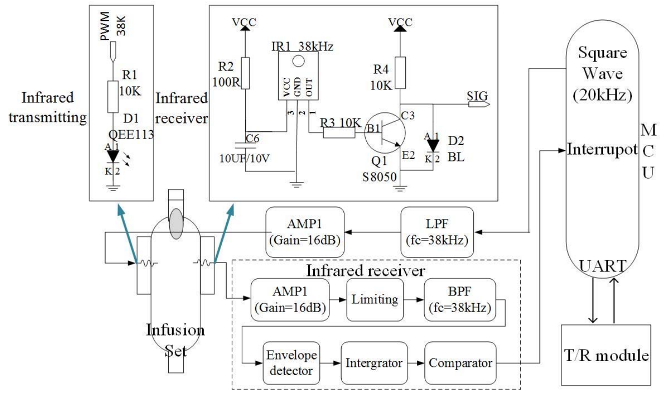

Fig. 4. Block diagram of the module of counting drops in the infusion monitoring terminal.

a three-wire infrared receiver, which are placed on the Fimos pot. The infrared emission tube outputs the 38 kHz infrared light wave from the MCU as a carrier wave. The receiver receives the infrared signal, sends it to the internal amplifier and limiter for signal pulse amplitude amplification and control, then it outputs an ac signal which will be dealt via the bandpass filter (38 kHz), demodulation circuit, integral circuit and comparator, and finally outputs a signal loading on the 38 kHz square wave. When the signal output by the infrared emission tube is not blocked by the droplet, it will be processed by the receiver which will produce a high voltage signal to the MCU. On the other hand, if the signal is blocked by a droplet, the receiver will produce a low voltage signal. Finally, the MCU uses its interrupt mechanism and a filtering algorithm to count the number of droplets dropping into the Fimos pot.

To the energy-saving issue of the monitoring terminal, we first use the interrupt detection process to reduce the occupied CPU time as the signal is more regular in the incoming single-chip. Then we formalize an intelligent sleep process to improve the energy efficiency. The monitoring terminal sends the data packets every 20 s and the communication module is set a low power state when it dose not work. The infrared optoelectronic is the main power consumption which works continuously to prevent the missing of drop counting. However, the time interval between two drops is not less than 300 ms because the maximum drop rate is not more than 200 drops per minute, so we can make the infrared optoelectronic to sleep 200 ms after monitoring a droplet. Finally, we set the port to the pull-down state to reduce the current consumption of high resistance when it does not work.

The generation and calibration of 32-bit CRC are performed, respectively, in the monitoring terminal and platform to ensure the integrity of packet. In addition, the monitoring terminal and platform use an unique key to achieve the identity using the RSA symmetric encryption.

2) Communication Scheme: We use NB-IoT to transmit data from the monitoring terminal to the monitoring platform. The development of the communication module contains the terminal development and the development of the application server, the flowchart of which is shown in Fig. 5. We deploy our application on an edge server which is used to collect data

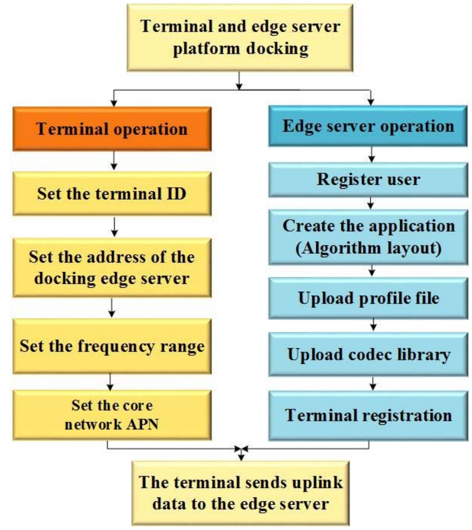

Fig. 5. Flowchart of NB-IoT end to end deployment.

from terminals, calculate the drop rate as well as the remaining drug volume and show the results to nurses. The development of the terminal side mainly contains the printed circuit board design of the hardware module and network access debugging, the development of edge server side mainly contains the profile file development, the codec library development and the application software development.

The profile is an abstract model of the terminal device, which abstracts the function of the terminal device as a service, and defines the service type and capability of the terminal device. There exits nonuniform application layer protocol between the terminal device and the edge server. To access devices, the edge server contains the codec package of the terminals. The edge server calls codec library according to the terminal ID and the model defined in the profile file.

NB-IoT further reduces the power consumption by introducing the entended discontinuous reception technique and power saving mode (PSM). NB-IoT saves power for the terminal which is online all the time by reducing unnecessary signaling and not receiving paging information when it is in PSM state. Our testes show that the communication module (Quectel bc95-b8) of the terminal consumes current of 3.6 uA in PSM state and 220 mA in long term evolution (LTE) Cat NB1 network connection. The average power consumption of the whole monitoring terminal is 12 mAh, which can make our monitoring device work continuously more than 90 h with two button batteries (CR2430).

Besides lower power consumption, our monitoring terminal is also low in cost, in which the cost of the single chip microcomputer–STMicroelectronics ST series 8 bit chip is about \$ 0.6, the cost of the NB-IoT communication module is about \$ 4.7, and the costs of the infrared tube and related accessories are about \$ 0.5. Using NB-IoT, the layout of the intermediate nodes required by the traditional communication like Wi-Fi and ZigBee is removed and the deployment cost is greatly reduced to about \$ 5.8 for the total cost of the monitoring terminal. On the other hand, it also greatly increases the scope and distance connected to the network for monitoring terminals.

The main purpose of the case study is to give a solution of the infusion monitoring problem required urgently in hospitals and verify the feasibility of using NB-IoT to connect all monitoring terminals. The infusion monitoring has no high requirement of latency with an acceptable 10 s delay. The maximum drop rate is no higher than 200 drops per minute and the existing drop coefficient is no less than 15 drops per milliliter, so the deviation of the remaining volume of drug is no more than 2.2 ml with a delay of 10 s, which is completely acceptable in the infusion monitoring system. The main challenges in the design of the infusion monitoring system are the energy consumption, the light interference and the calculation of the remaining volume, in which the latency is not given special attention. Still, by deploying the application on the edge server, the tested latency of the monitoring systems is less than 4 s.

3) Monitoring Platform: The main function of the monitoring platform is to calculate the drop rate and the remaining drug volume. We use M to denote the initial total volume of drug, N_t to denote the total number of drops in tth packet, and C to denote the drop coefficient of the infusion device which is the corresponding number of drops per milliliter drug, then the drop rate S can be calculated by

$$S = (N_t - N_{t-1})/20 \tag{1}$$

and the residual amount of the drug m can be calculated by

$$m = M - N_t/C. \tag{2}$$

To obtain the accurate drop rate and the remaining drug volume, we need to deal with two problems. One is to detect and repair faulty data transmitted from the monitoring terminal. The other is to estimate the drop coefficient. Due to the resource limitations of the monitoring terminal, communication interference, and other factors, the data transmitted from the monitoring terminal may be faulty. The distance-based fault diagnosis scheme is utilized to detect and repair faults. We first calculate the mean number of drops H during 20 s, and then estimate the probability distribution function of deviation of the number of drops in each 20 s to the mean value H. For each N_t, we calculate the probability p of $|(N_t - N_{t-1}) - H|$. If p is less than a preselected threshold δ, then N_t is diagnosed as a fault and repair as $N_{t-1} + H$.

The calculation of the remaining drug volume is based on the drop coefficient, which is affected by the viscosity of the liquid and the drop rate of the droplet. However, the main determinant of drop coefficient is the infusion device itself. The existing drop coefficient range of the infusion device is between 18.5 drops/ml and 21.5 drops/ml. Different infusion devices may have different drop coefficient, so the main issue of calculating the residual amount of the drug is to estimate the drop coefficient of infusion devices. Our approach is that we preset a mean drop coefficient 20 drops/ml of the infusion device for the first bottle, and from the second bottle, we estimate a more reasonable drop coefficient according to the estimated value of the previous bottles.

Algorithm 1 Drop Coefficient Learning Algorithm

Input: The number of bottles nb, and threshold of change for drop coefficients δ

Output: The drop coefficient $C_1, \cdots, C_{nb}$

```
G = ∅, C_max = 21.5, C_min = 18.5, F_1 = 20, δ = 1, n = 1;
while n < nb do
    if n ≤ 3 then
        We calculate C_n by equation (4);
        if |C_n − F_n| > δ then
            F_{n+1} = C_n;
        else
            F_{n+1} = F_n;
        end if
    else
        We select the center G_j of 𝒢_n with the most coefficients as F_{n+1};
    end if
    We cluster C_1, ..., C_n to k_n clusters 𝒢_n = {G_1, ..., G_{k_n}};
    n = n + 1;
end while
return C_1, ···, C_nb;
```

When the nth bottle of drug is completed, we calculate a drop coefficient of the infusion device C_n by

$$C_n = D_n/I_n \tag{3}$$

where D_n is the total number of drops of the nth bottle which can be obtained by the monitoring terminal, I_n is the infusion drug volume which is obtained by the initial total volume M_n of the nth bottle of drug minus the residual amount U_n when the nth bottle of drug is replaced. However, we cannot get accurate U_n because the staff may replace the drug at any time, so we suppose that there exists 10 ml drug when it is replaced and then calculate the drop coefficient by the nth bottle as follows:

$$C_n = D_n/(M_n - 10). \tag{4}$$

The calculated C_n may not be the actual drop coefficient because we do not know the actual the remaining drug volume when the drug is replaced. We should choose the C_i which has the highest probability of drop coefficients $C_1, \ldots, C_n$ as drop coefficient of $n+1$th bottle. However, each C_i may be various, so we use the k-means algorithm to classify drop coefficients $C_1, \ldots, C_n$ to k_n clusters $\mathcal{G} = \{G_1, \ldots, G_{k_n}\}$, and select the center of the class G_j with the most coefficients as the preset drop coefficient F_{n+1} of $n+1$th bottle. As special cases, we use $F_1 = 20$, if $|C_i - F_i| > \delta$ $(1 \le i \le 3)$, then the preset drop coefficient of F_{i+1} is set as C_i, otherwise, it is set as F_i. The specific algorithm is given in Algorithm 1.

For $C_1, \ldots, C_n$, the complexity of the k-means algorithm is $O(nkT)$, where k is the number of clusters and T is the iteration number of the algorithm, so the upper bound of the complexity of Algorithm 1 is $O((nb)^3T)$. The main factor affecting the calculation accuracy of drop coefficient is the remaining

TABLE I
REAL-TIME DROP MONITORING DATA

	The first bottle				**The second bottle**				**The third bottle**			
	Start	30min	60min	90min	Start	30min	60min	90min	Start	30min	60min	90min
Actual Drops	60	61	60	62	82	80	80	81	90	92	91	90
Display Drops	60	61	60	62	82	80	80	81	90	92	91	90
	The fourth bottle				**The fifth bottle**				**The sixth bottle**			
	Start	30min	60min	90min	Start	30min	60min	90min	Start	30min	60min	90min
Actual Drops	110	112	112	110	120	119	120	120	142	140	140	139
Display Drops	110	112	112	110	120	119	120	120	142	140	140	139

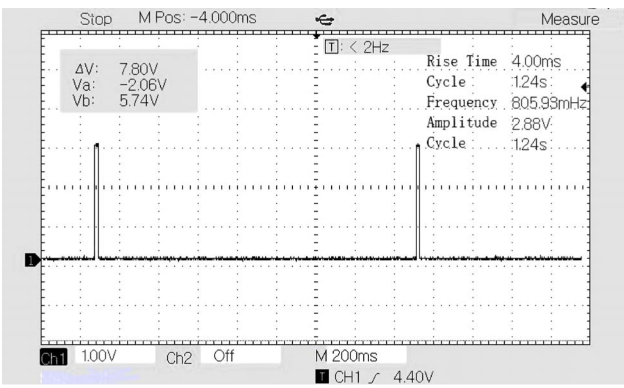

Fig. 6. Waveform of the monitoring terminal with strong light interference.

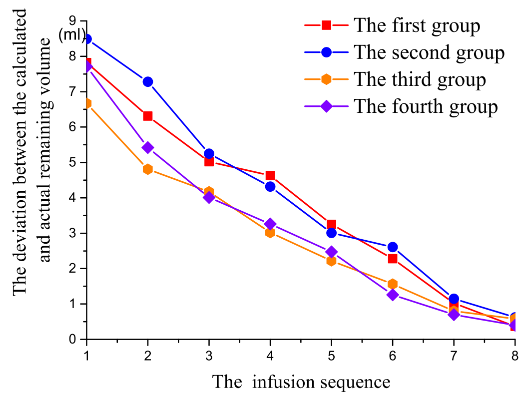

Fig. 7. Deviation between the calculated and actual remaining volume, which is shown in the y-axis when the calculated remaining volume is 10 ml for each bottle of drug.

volume when the drug is replaced. The nurse may not replace the drug when the remaining volume is exact 10 ml or the difference may be great. However, with the increase of the number of infusion bottles, the randomness of the remaining volume when the drug is replaced will gradually reduce, and the calculation error of the drop coefficient by Algorithm 1 will gradually decrease, which is indirectly verified by the following experiment.

D. Experiment Results

To verify the performance of our infusion monitoring system, we conduct three experiments. The purpose of the first experiment is to verify the performance of the monitoring terminal with strong light interference, the second experiment verifies the accuracy of drop counting of the monitoring terminal, and the last experiment verifies the accuracy of calculation of the remaining drug volume in the bottle.

1) Performance With Light Interference: We conduct the first experiment that the sun shines directly on the monitoring terminal at 2 o'clock to verify the accuracy of droplet acquisition of the monitoring terminal. The realization of droplet acquisition is based on the rising edge interrupt mechanism of the MCU, so the observation of the oscilloscope image can directly show the elimination of light interference. Fig. 6 gives the oscilloscope image of our experiment which shows clearly that the monitoring terminal can still produce very regular waves under the interference of strong light, which indirectly verify the accuracy of droplet acquisition of the monitoring terminal.

2) Accuracy of Drop Counting: We conduct the second experiment to verify the accuracy of drop counting by comparing the number of drops counted, respectively, by us and the monitoring terminal. We use a monitoring terminal to monitor six bottles of drug with different drop rates. For each bottle, we select four time points, respectively, as the start time, 30 min, 60 min, 90 min. For the experiment, we first clamp the infusion tube with a clip to suspend drug dropping, and then open the clip to start annual counting of drops in a minute when the monitoring platform continuously received two packets with the same total number of drops sum_0. Finally, we clamp the infusion tube again, wait until the monitoring platform receiving two packets with the same total number of drops sum_1, and compare whether sum_1-sum_0 is equal to the annual counting of drops to verify the accuracy of drop counting. The experimental results are shown in Table I, which tells us that the number of drops counted by the monitoring terminal matches exactly with the manual counting.

3) Calculating Accuracy of the Remaining Drug Volume: To verify the calculating accuracy of the remaining drug volume, we conduct an experiment of four groups of infusion monitoring. Each group test eight bottles of drug using our drop coefficient learning algorithm. Fig. 7 shows the deviation between the calculated and actual remaining drug volumes when the calculated remaining drug volume reaches 10 ml. In Fig. 7, the x-axis represents the experiment sequences of four groups, i.e., the experiments of the 1st, 2nd, ..., 8th bottle of drug. In the experiment for each bottle of drug, we first calculate the drop coefficient of the infusion device, then we count the total number of droplets when a data packet transmitted from the monitoring terminal and convert the number of droplets to milliliter using the calculated drop coefficient to calculate the remaining drug volume. When the calculated remaining drug volume is 10 ml, we suspend the infusion, draw out the drug in the bottle to measure its volume and calculate the deviation between the calculated and actual remaining drug volumes, which are shown in the *y*-axis of Fig. 7. From Fig. 7 we can see that 80% of the deviations are less than 5 ml, which is acceptable in the actual use, although the first bottle of each group has a large deviation, which indirectly verifies the accuracy of the drop coefficient learning algorithm.

V. Challenges and Future Directions

To connect intelligent things using the proposed architecture based on NB-IoT, there are still many challenges. We give the challenges and future directions to build a smart hospital using NB-IoT.

A. Accuracy and Reliability of Data

Accurate and reliable data collection is a major challenge in the building of smart hospitals. Current sensor techniques cannot achieve medical standards. For example, the accuracy of wearable devices cannot far reach the standard of medical devices and inaccurate data are valueless in medical applications, to which the sensor itself and the interference of the external environment are two main reasons.

Intelligent devices cannot exclude the interference which seriously affect the devices' measurement. For example, the change of the patient's posture may have a significant effect on the measurement of blood pressure. The measurement of the photoelectric can also be affected by the external light. In addition, the wearable device has great limitations on the wearable position and the measurement accuracy while bringing comfort and convenience to people. For example, the accuracy of blood pressure measured by the wristband with the photoelectric sensor cannot reach the level of the mercury blood pressure meter.

Due to the resource limitations, environmental factors and network attacks, data loss and faults of IoT devices are inevitable. Faults and missing data can lead to incorrect diagnosis or false alarms, which are fatal factors that affect the application of medical systems. The fault detection and reconstruction issue is another challenge in the building of smart hospitals. Common techniques include fault diagnosis based on probability and distance, fault diagnosis and reconstruction based on hidden Markov model, Bayesian network, clustering, classification trees, and so on.

B. Security and Privacy

Smart hospitals connect numerous IoT devices. The rich interfaces and large amounts of valuable data will attract attackers. Terminal devices and wireless communications are more vulnerable to cyber attacks, as the terminal devices cannot be able to run complex algorithms limited by the size and poor processing ability, and the wireless communication protocol need to pass a large amount of BSs and open wireless channels for data transmission which lead to easy data interception and replay. In addition, medical data may be related to the patient's life security, so security and privacy protection is a serious challenge to the smart hospitals. We need to improve the encryption mechanism of terminal devices, formalize reasonable encryption algorithm and key management mechanism to strengthen authentication, ensure the legal identity and prevent illegal nodes to send, forge, and tamper information. In addition, there should be a complete data backup mechanism to restore data in time when unexpected situations occur.

C. Wireless Communication Interference

Communication interference includes interference of external noise, interference of communication equipment's hardware, interference of network communication, and mutual interference between communication networks. Noise interference includes natural noise like lightning and manmade noise like medical equipment. These noises can interfere directly with the electromagnetic wave of wireless communication. The signals transmitted by the BS can interact with each other, which is more likely to cause blockage of the signal or interference of the same frequency and the adjacent channel. In a certain area, there are many types of networks, and the electromagnetic waves transmitted from different networks can interfere with each other. For example, NB-IoT can be deployed directly to global system for mobile communication, universal mobile telecommunications system, or LTE networks, which will inevitably interfere with other network communications [12].

The interference of wireless communication can result in data loss and faults. We must try to eliminate interference, reserve a backup transmission channel and introduce fault detection and data reconstruction schemes in the cloud platform to minimize data loss and faults caused by wireless communication interference.

D. Energy Consumption of Terminals

Terminal devices need to collect information with a high frequency and transmit data to the cloud platform with wireless communication. However, it is a major challenge for IoT devices to continuously work for a long time due to its limited size, low battery capacity, and the inability to constantly replace the battery or charge. There exist three directions to deal with this challenge.

The first direction is trying to reduce the energy consumption of terminals. We can improve the design process of sensors to enable it to maintain a low energy consumption without affecting its data collection accuracy. We can also use data fusion to reduce the amount of transmitted data. In addition, a low power protocol should be introduced to minimize the energy consumption of communication modules.

The second direction is the wireless charging technique. The cable charging has many troubles, e.g., when a patient is monitored by some medical devices, the cable charging can greatly limit the patient's activities. So we should develop the wireless charging technique which does not affect the monitoring process of the devices.

The third direction is the energy conversion technique. For example, when a device is outdoors, solar or wind energy can be converted to electricity, some piezoelectric elements can collect the mechanical energy produced by moving of the person and turn it to electricity. The energy conversion is sustainable for energy supply of IoT devices, which provides a new way to deal with the energy consumption issue.

E. NB-IoT Performance Testing

Compared to other communication protocols, NB-IoT is different in channel bandwidth, wireless channel type, frame structure and resource allocation methods, the corresponding idle mode, random access, radio resource control connection management, connection reconfiguration, wireless link monitoring, and possible redirection are also adjusted, which leads to that LTE testing instrumentation cannot be reused for NB-IoT. In addition, the access of large amount of terminals leads to that the existing terminals for multiterminal network testing and optimization cannot be used for NB-IoT. Therefore, how to use emulators for simulating terminals in different locations and different scenarios to test the network performance is a challenge for connecting monitoring devices in smart hospitals using NB-IoT.

F. Protocol Limitation of NB-IoT

In the future smart hospital, there are large amount of parameters requiring the monitoring with high real time and low latency. In our proposed architecture, the edge computing can reduce the communication latency in some degree. However, NB-IoT lacks the latency control mechanism in its protocol design, so it is a great challenge for the monitoring devices which have requirements of high real time and latency in smart hospitals. In addition, the diverse information display of new devices and the integration of multimedia techniques bring the demand for high bandwidth data transmission. However, NB-IoT protocol bandwidth is only 180 kHz now. The protocol limitation of NB-IoT is still a great challenge for its applications in smart hospitals.

VI. Conclusion

Due to the limitation of communication protocol, there exists non unified architecture that can connect all intelligent things in smart hospitals. In this paper, we first overviewed the application scenarios and characteristics of medical IoT devices in smart hospitals, and then proposed an architecture using NB-IoT. NB-IoT has drawbacks for applications which have high requirements of latency, so we introduced the edge computing in the architecture to reduce the latency of applications which were mainly deployed on edge computing and edge storage servers. As a case study, we designed an infusion monitoring system to monitor the real-time drop rate and remaining drug volume during the intravenous infusion using NB-IoT. Finally, we gave the challenges and future directions in building a smart hospital with NB-IoT.

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