A RFID-enabled Wireless Sensor Network (WSN) Monitoring System for Biological and Pharmaceutical Products

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Abstract—**Biological and pharmaceutical (B&P) products are essential and important for human being. In current era, the demand and requirement of these products are dramatically growing; product quality and integrity then become the most concerning part. As a key factor for ensuring the quality and integrity, the current product status monitoring system needs to be enhanced in a more sophisticated and comprehensive way. This research aims to design a Radio Frequency Identification (RFID) enabled Wireless Sensor Network (WSN) monitoring system for B&P products supply chain management. In this study, the basic design factors of a WSN are reviewed. It is found that battery capacity causes a bottle neck in the WSN. Therefore, system architecture is presented based on the proposed framework. The framework aims to develop a common approach to improve the energy efficiency of the WSN. It consists of three processes, the first one is to generate a WSN with full coverage; the second one is to determine the optimal position of the sink, and the last process is to add additional relay nodes for recharging or replacing the battery-exhausted nodes without affecting the network operation. Finally, a simulated case about B&P product storage in a hospital is conducted to show the overall procedures of the framework.**

Keywords-RFID, WSNs, biological and pharmaceutical (B&P) products, energy efficiency, coverage

I. INTRODUCTION

Biological products refer to nature substances obtained from living organisms [1]. Pharmaceutical products are drugs or traditional and modern medicines [2]. The supply chain of both types of products is a critical and essential portion in many different areas. However, managing biological and pharmaceutical (B&P) products supply chain is a challenging task since these products are highly susceptible to the variation of environmental factors, such as temperature, humidity, vibration, tilt, light and composition of atmosphere.

The general practice of handling B&P products applied in supply chain of Mainland China and Hong Kong is quite straightforward. The core locations in the supply chain, including factory, warehouse and distribution centre, utilize various equipment (i.e. refrigerators, heaters, air conditioners and sterilizers) to create and maintain an optimum environment for storing and processing the B&P products. When transportation between core locations is required, the B&P products are packed into insulated containers like adiabatic boxes and cooler chests to isolate the products from the external environment, and few of them are embedded with a thermometer or a temperature data logger [3]. However, the requirements of quality and integrity of B&P products become higher and higher nowadays, the current practice no longer meets the requirements since the equipment used in the supply chain rarely provide real-time and total reporting of product status. Therefore, this research proposes a Radio Frequency Identification (RFID) enabled Wireless Sensor Network (WSN) monitoring system to meet the emerging needs of B&P products supply chain management.

In the recent decades, WSN has raised significant attentions among researchers and practitioners. Plenty of applications from different areas successively emerge. Similar to many new technologies, there is a relatively high threshold to adopt WSN in industries. One of the most critical concerns is the energy efficiency, which is highly related to the system life time. Because of the usage of limited power source (i.e. battery), energy efficiency becomes a prior consideration when designing a WSN. Another critical concern is the number of sensor nodes. Although the cost of a single sensor node is relatively low, the amount of total production cost is unexpectedly high, especially for large-scale WSNs. Besides, the WSN should maintain a certain level quality of service (QoS), which usually is required by the users or applications. The QoS involves a series of quality metrics, such as data reporting rate, coverage degree and level of network connectivity.

This research aims to design and model a monitoring system based on RFID and WSN technologies. The main scope of this research focuses on designing and developing a monitoring system based on RFID and WSN technologies. The characteristics of B&P products decide that the storage environment should be consistent. As a result, charging or replacing batteries cannot be too frequent. The study area is to derive a common approach to make WSN run out of nearly all the batteries simultaneously while maintaining a high level of QoS.

II. LITERATURE REVIEW

WSN refers to a collection of sensor nodes with capability of wireless communication. These sensor nodes are generally small in size and low price, they have limited computational power and memory, and equipped with restricted power source (i.e. battery). In typical usage, sensor nodes are distributed into a target region and form a WSN. Each sensor node collects physical or environmental information of surroundings. The information collected

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will be sent to a base station (BS), which is also called sink and is a central information aggregation node. Through the sink, a backend system can store the gathered information and perform further analysis and process.

In case a monitoring area is large, hundreds, thousands and even more sensor nodes can be deployed on the site. Some factors are crucial for the deployment, which influence the design of WSN significantly. We reviewed the literature about energy efficiency, duty cycling and QoS.

A. Energy Efficiency

The sensor nodes in WSN are mainly powered by batteries with limited capacity. The exhausted batteries of some sensor nodes not only cause an information loss of some parts of the monitoring area, but also cause an operation disorder of the whole network and even cause a network collapse. Generally, a battery-powered sensor node cannot survive more than one week if the node always keeps active. Moreover, it is difficult to recharge or replace the batteries in most of the situations because of the harsh physical environment and the high maintenance cost [4]. In the last decade, researchers developed a plenty of approaches to improve the energy efficiency of WSN. One of the approaches is duty cycling [5].

B. Duty cycling

Duty cycling refers to switching the sensor node between active and sleep mode to conserve energy. Since the power consumption of the sensor node in sleep mode is significantly less than the active one. Duty cycling approach is believed to be the most effective way to conserve energy of WSN, since the sensor nodes only wake up when transmitting and receiving data and enter sleep mode when it is idle [4], [5], [6].

In WSN, topology determines the active states of nodes to fulfill certain requirements, for example, conversing network energy, avoiding collision and increasing network capacity [7]. In large-scale WSNs, such as the WSN for forest monitoring, the distances between some sensor nodes and the sink are large. It is energy-costly or infeasible to transmit data in single hop. This results the placement of relay nodes to route the data from remote sensor nodes to the sink. Besides data routing, relay nodes make contributions to many aspects of WSN, such as data aggregation, efficient transmission, network expansion, energy conservation and fault tolerance [8]. Relay nodes in a WSN can be some existing or additional sensor nodes with the same capabilities as the existing nodes and this type of WSN is called homogenous WSN. The relay nodes can also be some additional nodes with or without sensing ability and have larger communication and/or sensing range and larger power source. This type of WSN is called heterogeneous WSN [9].

C. Quality of Service (QoS)

QoS refers to a measure of service quality on the requirements from users or applications. In a WSN, QoS is important to deal with and it may be a series of performance metrics, such as coverage, connectivity, reliability, fault tolerance, data delay and data accuracy. However, QoS requirements vary from application to application. It is difficult to apply one pattern of QoS requirements to all WSN applications [10]. The key QoS requirements, which can be applied in most of WSN applications, include sensing coverage and network connectivity. These two factors are always considered together when designing a WSN since the coverage ensures the data collection from the region of interest while the connectivity ensures the path of data reporting from sensor nodes to the sink [11], [12]. If one of them is ignored, the WSN cannot be considered as a satisfactory solution for any application.

III. RFID-ENABLED WIRELESS SENSOR NETWORK (WSN) MONITORING SYSTEM

In this section, the conceptual system architecture is presented and the conceptual framework of the WSN management module, which is the core module of the system, is described.

The conceptual architecture of the proposed system is shown in Fig. 1, which consists of four layers, namely Information Acquisition Layer (IAL), Network Layer (NL), Logic and Processing Layer (LPL) and Service Output Layer (SOL). In IAL, the product state information and the environmental parameters (i.e. temperature, humidity and vibration) are collected by the wireless sensor nodes, which are widely spread in a large area like container, warehouse and distribution centre. The collected data is then routed to the data gathering and exchanging module (i.e. the sink of WSN) through Wireless Personal Area Network (WPAN). After that, the data is passed to Data Integration and Analysis Core (DIAC) in LPL through Internet via General Packet Radio Service (GPRS), Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX) or other wireless technologies. Before setting up the WSN, the user configuration, such as data reporting rate and technical specification of a type of B&P products, is injected into the LPL for configuring and fine-tuning the performance of DIAC and Wireless Sensor Network Management Module (WSNMM). In the DIAC, the data from NL is integrated with the RFID data and further analyzed for decision making. In addition, WSNMM is used to configure, manage the wireless sensor nodes and optimize their performance. The commands of configuration and management are passed back to the WSN control module in NL and all wireless sensor nodes are updated.

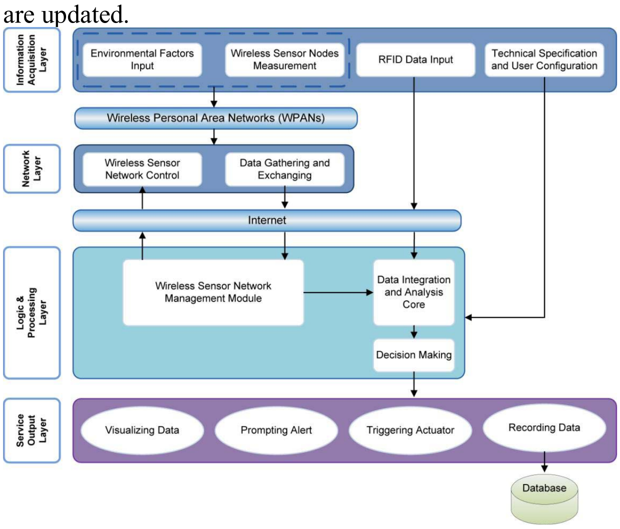

Figure 1. The conceptual system framework of the proposed system

As the WSN has deployed, SOL will be based on the decision made in LPL to deliver service outputs, including visualizing the data, prompting alerts when abnormal conditions occur, triggering operation of actuators and storing the collected and processed data in the database for querying and further analysis in the future.

The proposed framework focuses on dealing with heterogeneous WSN, which the WSN consists of both sensor and relay nodes. The sensor nodes are supposed to switch between sleep and wakeup mode to conserve energy when they are idle. The WSN management module contains three processes. In the first process, a WSN model is formulated by considering the sensing coverage and network connectivity. The sensor nodes are defined as a sensor nodes set $S = \{s1, s2, ..., sn\}$ and each sensor has the same sensing range rs and communication range rt. Similarly, the relay nodes are defined as $T = \{t1, t2, ..., tn\}$ with the same communication range Rt which is larger than rt. For a space point p in the monitoring area, it is covered by at least one sensor node. This coverage constraint can be represented as:

$$\sqrt{(sj_x - p_x)^2 + (sj_y - p_y)^2} \le r_s \cdot \quad (1)$$

where (sj_x, sj_y) and (p_x, p_y) are the Cartesian coordinates of a sensor node sj and a space point p. On the other hand, each sensor node in the WSN is also covered by at least one relay node. This can be represented as:

$$\sqrt{(s1_x - tj_x)^2 + (s1_y - tj_y)^2} \le r_t \cdot \quad (2)$$

where $(s1_x, s1_y)$ and (tj_x, tj_y) are the Cartesian coordinates of a sensor node $s1$ and a relay node tj. Moreover, between each pair of relay, there should be a path shorter than the communication range of relay node. It can be represented as:

$$\sqrt{(ti_x - tj_x)^2 + (ti_y - tj_y)^2} \le R_t \,. \quad (3)$$

As the relationships between the nodes in the WSN are built up, next step focuses on calculating the number of sensor nodes and the relay nodes. The objective is to obtain the minimum number of sensor nodes that the total sensing range covers all the space point in the monitoring area.

In the next process, the position of the sink is considered. The sink is suggested to be located at an optimal place that the total power consumption of all the relay nodes for data transmission is the minimum [13]. In other words, it means that the total distance between each relay node and the sink should be minimized because the power consumption is proportion to the distance between a transmitter and a receiver. This can be represented as:

$$(x_0, y_0) = \arg\min_{(x,y)} \sum_{i=1}^{N} \sqrt{(ti_x - b_x)^2 + (ti_y - b_y)^2} \cdot \quad (4)$$

where (b_x, b_y), (ti_x, ti_y) and (x_0, y_0) are the Cartesian coordinates of a sink b at an initial position, a relay node ti and the sink (i.e. b) at the optimal position. N is the total number of relay nodes in the WSN.

After going through the first two processes, a complete WSN is constructed. In the last stage, additional relay nodes are inserted into the WSN to make a balance of battery capacity for the network. The additional relay nodes are deployed around the existing relay nodes and stay in sleep mode to conserve energy. Once a relay node runs out of energy, an additional node in neighbour will wake up and substitute the functionality of the original one. Furthermore, the number of the additional relay nodes is calculated at this stage.

Firstly, the monitoring area is divided into n regions based on coverage area of the relay nodes. Then, the number of days of different area usage rate is counted in a period that the batteries are expected to be recharged or replaced. The area usage rate refers to how many regions are used for inventory storage. For example, the days in period 1 which the area usage rate stays above 0, $1/n$, $2/n…n$-$1/n$ is counted respectively using statistics, where n is the total number of relay nodes. The results are represented as $D_{11}, D_{12},...,D_{1n}$, where n is the total number of relay nodes. Since one sample is inadequate, the day counts are recorded in the successive period 2, 3…until the sample size is statistically reasonable. In the next step, the mean and standard deviation of a region k can be calculated as:

$$\overline{D_k} = \frac{D_{1k} + D_{2k} + ...D_{mk}}{m} \,. \quad (5)$$

where, m is the number of periods counted.

$$\sigma_k^{\ 2} = \frac{m-1}{m} \sum_{i=1}^{m} (D_{ik} - \overline{D_k})^2 \cdot \quad (6)$$

Based on the data, the normal distribution of D_k can be built.

$$f(D_k, \overline{D_k}, \sigma_k^{\ 2}) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{(D_k - \overline{D_k})^2}{2\sigma^2}) \cdot \quad (7)$$

The reliability level should be guaranteed to be larger than r.

$$F(D_k, \overline{D_k}, \sigma_k^{\ 2}) \ge r \,. \quad (8)$$

Then, the number of relay nodes in space k can be represented as:

$$N = \left\lfloor \frac{D_k}{E} \right\rfloor - 1 \cdot \quad (9)$$

where, N represents the additional number of relay node, and E represents the days the relay nodes can survive when it is active.

IV. SIMULATION STUDY

In this section, a simulated case is studied to describe the operating procedure of the proposed system.

There is a storage room for B&P products in the hospital studied. First, the RFID-enabled WSN is installed in the room. According to the previous section, the procedure is divided into three steps. Firstly, the sensor nodes and relay nodes are deployed to cover all the area in the storage room applying formulas (1)-(3). The results are shown in Fig. 2. Secondly, formula (4) is used to decide the optimal location of the sink. Then, an investigation is made to find whether the room is always full of store. If the store room is not always full of store, the installment is then finished. Otherwise, some additional relay nodes should be added. In this case, there are 18 sensor nodes and 5 relay nodes. The room is divided into 5 regions. The days of the inventory level that stays above 0%, 20%, 40% 60% and 80% are counted. The period for replacing batteries is one month (30-31 days). The historical inventory information of last year is used for statistics. The reliability is set as 99.5%. After calculating by formulas (5)-(8), D1=31 D2=27 D3=21 D4=14 D5=6. The average number of active working days for the chosen battery is 6. Applying formula (9), the additional relay nodes in each area can be decided. The results are respectively 5, 4, 3, 2 and 0. The region with the highest number of additional relay nodes is set as region 1. It has the highest priority to store products, and then region 2, which the number of additional relay nodes is less than region 1 but more than region 3 and 4, and finally the region 5, which there is no additional relay nodes. At first, all the additional relay nodes are at sleep status. The relay nodes not being used are also set as sleep status in the region that no inventory stored.

After deployment of WSN, the system works to collect data. In this case, the main work is to monitor the temperature changes in the room. Once abnormal temperature is detected, the system will prompt warnings to the users. Then, the hospital can take immediate actions to avoid accidents.

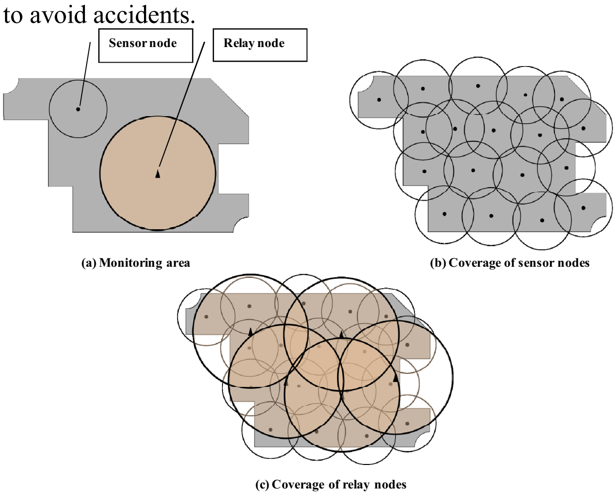

Figure 2. The coverage of sensor nodes and relay nodes in a WSN

V. CONCLUSIONS

Adopting WSN technology requires consideration of a series of design factors, including energy efficiency, sensor nodes placement, sensing coverage and network connectivity. To manage these factors effectively, a three-stage framework is proposed. In the first stage, a minimum number of sensor nodes and relay nodes is placed and fully covered the monitoring area. Next, the sink is put in an optimal place that the total transmission power of all the relay nodes can be minimized. Lastly, the number of additional relay nodes is calculated, in order to balance the battery capacity of the relay nodes in a WSN. The proposed approach uses statistics to calculate the number of the additional relay nodes needed in a targeted area. Finally, a simulated case is studied to show the work procedure and functions of the system.

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