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RFID analytics for hospital ward management

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Abstract In this paper, we present an RFID-enabled platform for hospital ward management. Active RFID tags are attached to individuals and assets in the wards. Active RFID readers communicate with the tags continuously and automatically to keep track of the real-time information about the locations of the tagged objects. The data regarding the locations and other transmitted information are stored in the ward management system. This platform enables capabilities of real-time monitoring and tracking of individuals and assets, reporting of ward statistics, and providing intelligence and analytics for hospital ward management. All of these capabilities benefit hospital ward management by enhanced patient safety, increased operational efficiency and throughput, and mitigation of risk of infectious disease widespread. A prototype developed based on our proposed architecture of the platform was tested in a pilot study, which was conducted in two medical wards of the intensive care unit of one of the largest public general hospitals in Hong Kong. This pilot study demonstrates the feasibility of the implementation of this RFID-enabled platform for practical use in hospital wards. Furthermore, the data collected from the pilot study are used to provide data analytics for hospital ward management.

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1 Introduction

In the era of big data, companies and organizations are able to capture, process, manage, and analyze large volumes of data and turn them into valuable information and managerial insights that can help design better products, enhance service quality, improve operations, and make decisions. Big data analytics not only supports businesses and commercial organizations to create further profits, but also helps governments and public sectors with providing high-quality services to citizens, and consequently benefits the populations by enhancing the quality of life. Although many sectors like retail and banking have already embraced big data for many years, the healthcare industry has lagged behind them due to several reasons, such as medical service providers' resistance to change, underinvestment in information technology because of uncertain returns, security issues, and patient privacy concerns (Groves et al. 2013; Kayyali et al. 2013). While there are various barriers to utilize big data in the healthcare industry, without a doubt big data can substantially benefit the healthcare stakeholders, for instance, by conducting comparative effectiveness research, developing clinical decision support systems, remotely monitoring patients, promoting personalized medicine, and analyzing disease patterns (Manyika et al. 2011). In this paper, we present a platform, which is based on radio-frequency identification (RFID) technology, for hospital ward management. With a prototype developed based on the architecture of this platform, a pilot study was then conducted in two medical wards of the intensive care unit of one of the largest public general hospitals in Hong Kong to demonstrate the feasibility of its practical use.

Prior to the introduction of RFID technology to the healthcare industry, healthcare facilities had to keep track of patients and valuable assets manually, or by the use of barcoding; the adoption of RFID in healthcare management has facilitated those practices. RFID has advantages over barcodes; barcodes have to be scanned manually one at a time within the line of sight of the reader, while multiple RFID tags, even if they are covered by some other objects, can be detected automatically and simultaneously by an RFID reader, whose read range is longer than the read ranges of barcode scanners. This automated process can save labor hours for performing some hospital routine tasks. The time saved from these non-value-added activities can help to reduce operational costs, or be transferred to provide additional professional services that can benefit patients. RFID not only reduces healthcare expense, but also facilitates automating and streamlining patient identification processes in healthcare operations (Chowdhury and Khosla 2007). The identification processes can help to reduce medical errors and mitigate patient risk. Overall, those healthcare facilities which had implemented RFID believed that the technology has more advantages than disadvantages (Reyes et al. 2012).

Our work was motivated by the outbreak of Severe Acute Respiratory Syndrome (SARS) in Hong Kong. In the incident, a significant number of individuals, including patients and hospital staff, were infected with SARS within a hospital. A project team from the Chinese University of Hong Kong (CUHK) considered the deployment of RFID technologies to trace the physical contacts of individuals within the wards in case of an infectious disease outbreak, in order to immediately and effectively isolate potentially infected individuals to mitigate the risk of disease widespread. Although many healthcare professionals around the world have put enormous efforts into avoiding cross-infection among people in healthcare facilities since the SARS outbreak in 2003, risk mitigation of infectious disease in healthcare settings appears to be not very effective. It is not uncommon that individuals working in or visiting a healthcare unit are infected by some disease carriers. For example, the recent outbreak of Middle East Respiratory Syndrome (MERS) in South Korea, where most of the infections took place in health facilities (BBC News 2015), has again raised public worry about the spread of infectious disease in healthcare settings and has further affirmed the importance of tracing physical contacts between individuals in order to quickly and effectively isolate individuals suspected of carrying MERS. The goal of the project presented in this paper is to develop a platform that enables traceability of individuals in healthcare settings. In addition to the traceability, our proposed platform also benefits the healthcare stakeholders by enhanced patient care, and increased operational efficiency and throughput.

Our paper is organized as follows. In the next section, we give a literature review on the use RFID for healthcare applications. In Sect. 3, we describe the main components of our proposed platform, its architecture, and its benefits to hospital ward management. Section 4 provides the details of the pilot study and presents the capabilities and analytics that we can obtain from the RFID tracking data. Section 5 concludes our work.

2 Literature review

RFID has been widely applied in numerous industries, including aviation (Wyld et al. 2005), construction (Wang 2008), food retailing (Jones et al. 2005; Moon and Ngai 2008), logistics (Jones and Chung 2007), and supply chain (Angeles 2005; Prater et al. 2005; Tajima 2007; Sarac et al. 2010). RFID applications not only have practical contributions to optimizing operations in business and public sectors, but also have research values; in particular, academic journals in the field of operations and processes management such as *Production and Operations Management*, *International Journal of Production Economics*, and *International Journal of Production Research* devoted special issues to papers of real-life RFID applications (Dutta and Whang 2007; Ngai and Riggins 2008; Ngai 2010). For overall RFID applications, literature review, and future research, we refer the reader to Chao et al. (2007), Ngai et al. (2008), Liao et al. (2011) and Zhu et al. (2012). Although RFID technology has been widely applied in many industries, its adoption in the healthcare industry is still far behind from others due to various reasons, such as long payback periods, the need to modify the existing processes, the lack of applicable standards (Reiner and Sullivan 2005), and privacy and security concerns (Rosenbaum 2014). For recent reviews of literature on the adoption and implementation of RFID technologies in the healthcare industry, we refer the reader to Health Industry Business Communications Council (2012), Wamba (2012), Yao et al. (2012), Coustasse et al. (2013) and Wamba et al. (2013).

There have been various successful RFID-enabled applications in the healthcare industry. A major proportion of work deployed RFID to reduce medical mistakes or errors, which aims to improve patient safety. Medical mistakes are the third leading cause of death in the United States (Hospital Safety Score 2013) and are estimated to cause 440,000 preventable deaths of patients (James 2013). Among all kinds of medical errors, misidentification is a major source (Yao et al. 2012). Positive patient identification (Aguilar et al. 2006), which requires each patient to wear a RFID wristband that contains the patient demographic information, has been proposed to provide a solution for reducing those errors due to patient misidentification. Dalton and Rossini (2005) used RFID technologies to avoid blood transfusion errors. The staff members of the blood donation centre used RFID readers to scan the RFID wristbands of patients and checked with their PDAs if the information is identical with the blood bag tag. Fuhrer and Guinard (2006) developed a web-based application, which is called the RFIDLocator, to track and locate patients. The system made sure that the correct operation is performed on the right patient at the right operating theater. Yen et al. (2012) proposed two RFID-based solutions to reduce inpatient medical errors by nurses. An offline solution was proposed for the use in a hospital environment that does not support wireless communication. The nurses had to download the latest inpatient's prescription records from the system at the nurse station to their PDAs before visiting their patients, and to upload the their drug administration records from their PDAs to the system after their visits. An online solution was proposed for the use in an environment that wireless communication is enabled, so that the nurses could download and upload real-time drug administration information from and to the system at any moment. For both solutions, the nurses used their PDAs, which were equipped with an RFID reader, to read the RFID tags in the wristbands of the patients and in the corresponding unit-dose packages to eliminate medication errors during drug administration tasks.

In addition to positive patient identification, there are also other applications of RFID to reduce medical mistakes. Kim et al. (2006) used RFID and sensor network to restrain blood deterioration during transportation. RFID tags were attached to blood bags to track their locations, and continuously monitor their temperatures to ensure that the blood samples are suitable for transfusion. Reicher et al. (2007) demonstrated the use of RFID for preventing improper positioning of the endotracheal tube, where an RFID tag was secured, during intubation. Francis et al. (2009) deployed RFID to limit the incidences of mislabeling tissue specimen bottles in gastrointestinal and colorectal surgery endoscopy units. Pleteršek et al. (2012) developed an automatic disinfectant tracker that verifies the disinfection of the hands of medical staff, patients, and visitors in hospitals. A smart active label, which was capable of measuring and recording the time stamp of application, its duration, temperature, and ethanol concentration, was used to transmit the information to readers. They proposed two methods, differential dynamic method and static disinfection control, to monitor hand disinfection of people in hospitals. To fight against drug counterfeiting, pharmaceutical companies have also deployed RFID for drug packaging and labeling to prevent fake products from entering their supply chains (Young 2004).

Another way of deploying RFID to enhance patient safety is to detect patients' adverse events, which can potentially be fatal to patients. Lin et al. (2008) applied RFID to monitor dementia patients in both indoor and outdoor environments. Their developed system will warn caregivers whenever a patient is within a dangerous zone or strays too far. Yao et al. (2011) proposed complex event processing to manage large volumes of RFID data, detect medically significant events for context-aware applications, and model surgical events and critical situations. Al-Masri and Hamdi (2015) introduced an RFID-based system, called RFIDTrack, to continuously monitor patients. The system would alert the medical staff, by sending a text message, in case of any early detection of adverse events (e.g., a steady rise in the body temperature, abnormal heartbeats, and improper movements of a patient).

Besides monitoring patients, asset tracking is another popular application of RFID in hospitals. The benefits include increase in resource utilization and prevention of losses of equipment. Østbye et al. (2003) conducted a prospective controlled evaluation in two similar hospital wards, where one ward used an asset-tracking system enabled by infrared signals and radio frequency while the other did not. They found that utilization of infusion pumps was higher in the ward that adopted the system. Hakim et al. (2006) adopted a passive RFID system to track assets in a hospital in Connecticut. The system aimed to monitor the telemetry transmitters in the hospital and prevent people from stealing them. Mun et al. (2007) deployed RFID to track hospital assets such as infusion pumps, beds, and wheelchairs. They integrated their RFID asset management system with 2D barcode technology to improve processes in the hospital and patient safety, and reduce operational costs. Shirehjini et al. (2012) proposed an RFID-enabled system that integrates tags into the floor and mounts readers on objects to determine the locations of mobile objects in a hospital. They used basic vector operations to achieve a better measurement of position and orientation of an object. The system can monitor the medical equipment and high-risk patients.

RFID has also been demonstrated to be an effective technology to optimize healthcare operations. Fry and Lenert (2005) presented a real-time asset location system that used RFID to track patients, equipment, and staff for supporting operations and decisions during mass casualty events. The system provides tag position information, and data from medical information systems, registration applications, and the US Navy's TACMEDCS triage application, which facilitated emergency response. Miller et al. (2006) used RFID to collect data on activity durations at a hospital emergency department. The data were then used to model processes in the simulation model of the emergency department. Magliulo et al. (2012) presented an approach that combined RFID locating system and electronic medical management systems to optimize the patient flow of a radiotherapy department. Parlak et al. (2012) demonstrated the feasibility of using RFID to track tools, recognize trauma team, and hence to support fast-paced and complex teamwork in a trauma center. Marchand-Maillet et al. (2015) developed an RFID-based system to record the time spent by patients between their admission and discharge from an academic ambulatory surgery center; the data were then used to construct operating room schedule.

RFID can also save healthcare operational cost and reduce system inefficiencies. Bendavid et al. (2012) presented a case study of applying an RFID-enabled traceability system for managing consignment and costly items in an operation room environment. They showed that their system together with the redesign of replenishment processes could facilitate item-level traceability and inventory management, upgrade service levels, and increase time for patient care activities by saving time from non-value-added activities. Romero (2014) showed that an RFID-barcode identification system could reduce inefficiencies in pharmacy operations, such as poor inventory management, medicine shrinkage, intensive manual labor, long procurement cycles, and time-consuming product recalls. Kumar and Rahman (2014) conducted a case study of a Singaporean hospital, which demonstrates that the usage of an RFID system could provide clear visibility in linen stock control.

Although there have already been various healthcare applications of RFID, most of them are implemented at an operational level, while the data generated by RFID systems are seldom analyzed. Furthermore, staff at hospitals were rarely tracked in those applications. In this paper, we present an RFID-enabled system that can provide additional capabilities by tracking patients, ward staff, and medical assets. We also present a pilot study that we utilize the RFID data for establishing traceability of resources at hospital wards.

3 An RFID-enabled platform for high-quality inpatient care and risk mitigation in hospital wards

RIFD is a technology that uses electromagnetic fields to transfer data. The purposes of RFID are mainly to automatically identify objects and keep track of their locations over time. An RFID-enabled application consists of two components of hardware—tags and readers—and a middleware. An RFID tag contains electronically stored information, such as its unique tag serial number and object-related information, and is attached to an object (products, assets, and even individuals), when in use. Information stored on a tag can be updated, or locked. RFID tags can be active or passive. An active tag requires internal battery to power the tag and transmits signal periodically, while a passive tag has no internal battery and relies on the radio energy transmitted by an RFID reader to power the tag. Therefore, passive RFID requires stronger signal strength, compared to the signal strength to operate active tags. In general, active RFID has a longer read range (i.e., the range that a tag and a reader can communicate) than passive RFID (more than 100 meters for active RFID; around 3 meters for passive RFID), but is more expensive (USD 15 to 100 for an active RFID tag; USD 0.15 to 5 for a passive RFID tag) (Jovix 2015). Passive RFID is mainly used for identification, while active RFID is mostly applied to track objects. The principle of RFID can be briefly described as follows. When a tagged object falls within the read range of a reader, the reader will transmit an encoded radio signal to interrogate the tag of the object. After the tag receives the signal, it will transmit an identifier and some other specific information, depending on the application, to the reader. The reader will then deliver the information to the middleware. In most applications the middleware is integrated with the legacy computer system of the application. The transmitted information is delivered from the middleware to the computer. The system will then create a unique ID and a timestamp for this record and store the transmitted information. Users can therefore retrieve the up-to-the-minute information, e.g., locations, regarding the tagged objects from the computer system. RFID data stored in the computer system can also be analyzed offline. For example, aggregating all the observations transmitted over time, the computer system can help to trace the location of any tagged object at any time. This helps to obtain the information about "who or what is where, and when".

Here, we present the concept and architecture of an RFID-enabled platform for hospital ward management, which aims to provide inpatient care of higher quality, reduce patient risk, and optimize operations. A prototype developed based on this architecture was also tested in a pilot study, which will be described in detail in Sect. 4. The development of this platform aims to deploy a set of RFID technologies, which most hospitals are able to afford, for hospital wards management and achieve the following goals:

1. To strengthen the care coverage of inpatient treatment;
2. Reduce risks incurred during inpatient period;
3. Analyze ward activities and interactivities.

With active RFID technologies, objective (i) can be actualized by real-time tracking of patients' locations and monitoring their health statuses, objective (ii) is achieved by patient identification and tracing paths of hospital-acquired infections, and objective (iii) is done by analyzing automated, continuous streams of tracking records.

Similar to other RFID-enabled applications, the architecture framework of our proposed system requires the three major components: RFID tags, RFID readers, and a middleware. The middleware can be integrated with the legacy ward management system of the hospital so that ward staff are able to retrieve real-time information related to all objects in wards to facilitate operations. We use active RFID technology for continuous tracking purposes. Active RFID tags are attached to the objects in the hospital wards. In addition to patients, the tagged objects also include ward staff and medical equipment, which empowers additional capabilities and allows us to generate further insights into the interactions among the three categories of objects. Each object is registered in the computer system and is given a unique ID which makes each of them identifiable. Patient personal information (name, gender, age, etc.) and case history are also available in the ward management system so that hospital staff can retrieve the information whenever necessary. This application of RFID technologies can also eliminate the traditional physical constraint that patients' health monitoring devices must be physically connected to the hospital legacy system to transmit patients' health-related data. Due to the recent technological advancement, these health monitoring devices have become smaller and lighter so that they are portable and wearable. For example, Microsoft Band is a light wristband with multiple sensors installed and has the capabilities of continuously monitoring heart rate, body movement, skin temperature, and galvanic skin response. Such wearable health monitoring sensors can be connected to an RFID tag to establish linkage for health-related data transfer. Once data about health status have been transmitted from the sensors to the RFID tag, all real-time information regarding the corresponding patient (e.g., location and health status) can be sent from the tags to the readers via radio frequency data communication continuously. The real-time information is then delivered from the readers, via the middleware, to the ward management system for processing and storing the data. From the ward management system, ward staff would be able to locate each objects on the map at any moment, and monitor the health statuses of patients. For offline use, the stored data can also be used to report ward statistics and provide insights, intelligence, and analytics to hospital administrators for future planning. Figure 1 depicts the flow of our proposed RFID-enabled platform. Our proposed platform can facilitate hospital ward management at both operational and analytical levels by the capabilities of real-time monitoring and tracking of individuals and assets, reporting of ward statistics, and providing intelligence and analytics. Below we describe the benefits of our proposed RFID-enabled platform to the healthcare stakeholders.

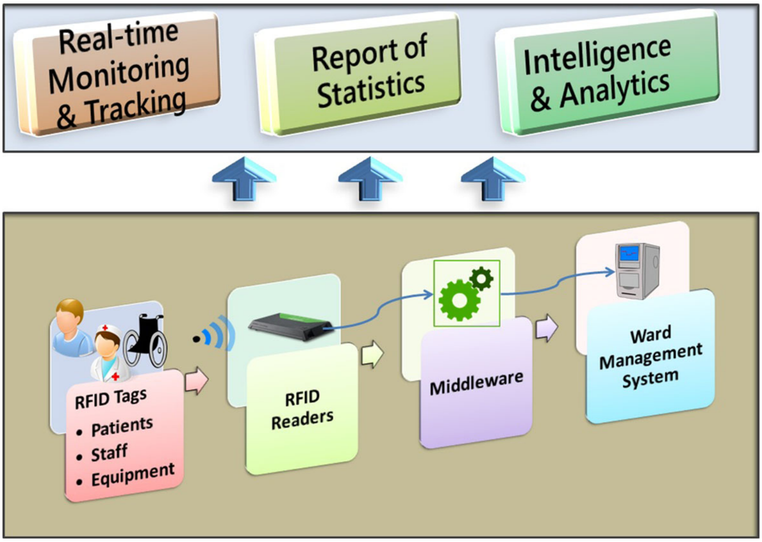

Fig. 1 The major components of the RFID-enabled platform and its flow

3.1 Enhanced patient safety

The main advantage of deployment of this platform is the enhanced patient safety. First, the system can improve compliance by avoiding medication errors due to misidentification of patients, for instance, a wrong dose, drug, or medical treatment is given to a wrong patient. To avoid such errors, nurses can use portable electronic devices, e.g., PDAs, smart phones and tablets, equipped with RFID readers to obtain the accurate personal information from the tag attached to the patient to verify his/her identity, and confirm medication or medical treatments. A record will also be created in the system after the patient has finished his/her assigned dosage taking process or medical treatment to improve regulatory compliance. Second, the system enables patient tracking; ward staff will be notified immediately whenever a patient is within a dangerous area or a suicidal patient leaves the ward. Third, ward staff will also be alerted if the patients are in dangerous conditions, by real-time monitoring their health statuses and body motions (e.g., falling).

3.2 Increased operational efficiency and throughput

Another advantage of the adoption of this platform is increased operational efficiency and throughput. Some paperworks and manual processes for inputing data into the system and can be automated by the data capturing and storage features of the platform. This automated procedure also reduces human errors and, thus, contributes to enhanced patient safety. Moreover, by the asset tracking capability, ward staff can easily and quickly locate their required medical equipment. This can save a significant amount of time from searching for the equipment and can transfer the saved time from this kind of non-value-added activities to services that provide additional professional care to patients. Furthermore, the data collected in the system related to staff and equipment activities in the wards can provide hospital administrators with insights into manpower and resource planning. The data can reflect the usage durations for different classes of staff and equipment. Hospital administrators can therefore calculate the utilizations of different types of resources, identify scarce resources, and determine their optimal levels for future use. Hospital administrators can also look at the activities of ward staff at different time periods on different days of the week to determine a better work-shift schedule. At an operational level, the capability of asset tracking prevents theft losses of valuable medical equipment.

3.3 Infectious disease risk mitigation

Last but not least, the platform enables infectious disease traceability in hospital. The locations that patients visited at every moment were recorded in the ward management system. In case of an infectious disease outbreak within the hospital, the hospital management can quickly trace back the person-to-person physical contacts by retrieving, from the ward management system, the data about the locations and times that the (confirmed and suspected) disease carriers visited in the incubation period and a list of individuals who visited the same locations at the same times. This provides a way such that the hospital can promptly and effectively isolate those potentially infected individuals to mitigate the risk of disease widespread. Furthermore, the traceability also enables the hospital to figure out the spreading paths and source of infection, which is exceedingly helpful for infectious disease control. In most of the RFID applications in the healthcare domain, tags are attached to patients or hospital assets; hospital staff are rarely tagged objects. In our proposed platform, hospital staff are also tagged because they can also be infected by disease carriers within the hospital when providing medical cares.

In the next section, we will describe the prototype that was developed based on our described architecture and our pilot study.

4 Case study: tracking of patients, personnel and assets in two RFID-enabled hospital wards

4.1 Background and motivation

In 2003, an outbreak of SARS, which is a viral respiratory disease caused by the SARS-associated coronavirus (Peiris et al. 2003), resulted in a total number of 8,096 confirmed cases and 774 deaths in multiple countries and cities around the globe (World Health Organization (WHO) 2004). Hong Kong was the city suffering most from SARS; there were 1,755 cases and 299 deaths reported in the period of outbreak (WHO 2004). The SARS epidemic in Hong Kong began in the Prince of Wales Hospital (PWH) in Hong Kong five days before WHO announced that there were numerous cases of acute respiratory syndrome with unknown aetiology reported in the area of the southern part of the People's Republic of China (SARS Expert Committee of Hong Kong SAR Government 2003). Before WHO announced the outbreak of this deadly disease and placed a high alert on the situation, the hospital management of PWH had already suspected that there was a communicable disease outbreak within the hospital when eleven medical staff members working in the same ward reported sick leave simultaneously. Although PWH had eventually identified the index case-patient and then immediately isolated this patient and other infected carriers, a total of 239 individuals, including medical staff, students, patients, and visitors, were cross-infected with SARS in PWH due to the unawareness of this previously unknown disease when this patient was admitted (SARS Expert Committee of Hong Kong SAR Government 2003). After the outbreak of SARS, a project team from the CUHK considered the feasibility of using RFID technology to enable traceability for person-to-person physical contacts in order to provide immediate response to the widespread of infectious diseases and better risk management within hospital wards. In case of confirmed or suspected cases of infection, the hospital management can easily and quickly trace back the contacts between people in the wards, by retrieving the data about the locations the infected patients had visited and listing the individuals who visited those places at the same times, from the ward management system.

Healthcare-associated infection, i.e., infection acquired in healthcare facilities, is not a rare incidence that only took place during the outbreak of SARS in Hong

Kong, but the most frequent adverse event in healthcare delivery systems all over the world (WHO 2013). Infectious disease outbreak by cross-infection among individuals in health facilities is also a kind of healthcare-associated infection. Such cross-infection can be difficult to prevent as carriers of some deadly infectious disease may only show mild symptoms (such as fever, cough, and muscle pain) at an early stage after being infected so that medical staff are not able to identify these carriers and isolate them in the first place. The outbreaks of SARS in Hong Kong and MERS in South Korea are examples of cross-infection of deadly diseases among people in healthcare settings. Since an effective and prompt isolation of potentially infected individuals can substantially mitigate disease widespread, the project team of CUHK aimed to apply advanced technology to facilitate the isolation procedure.

The project team conducted a pilot experiment PWH to study the feasibility of the implementation of the RFID-enabled platform for hospital ward management. PWH is one of the largest public general hospitals in Hong Kong and also the teaching hospital for the Faculty of Medicine of the Chinese University of Hong Kong. It has around 1,500 hospital beds and 4,500 staff, and serves the region of New Territories East (more than 1.5 million people). In particular, the experience that the hospital management and medical staff had gained during the outbreak of SARS and their advice were very valuable and exceedingly helpful when designing this platform. This motivated the project team to select wards at PWH to conduct this pilot study and demonstrate its practicality.

Two medical wards, named Ward 1 and Ward 2 in the rest of this paper, of the intensive care unit of PWH were selected to implement this pilot project. Each ward was subdivided into different zones, where active RFID readers were installed at the corners of each zone. Therefore, there were at least four RFID readers used to locate each object with a high accuracy of the location data. The active RFID readers and tags, that were used to track the locations of the objects, were manufactured by the Department of Electronic Engineering of the Chinese University of Hong Kong.

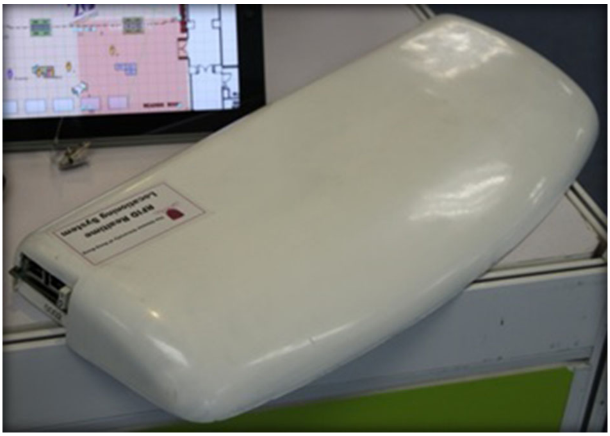

Fig. 2 An RFID reader that was installed in a ward of our study

Figure 2 shows an RFID reader that was used in this project. The tags were attached to the patients, caregivers, and equipment (infusion pumps, cardiac meters, oxygen cylinders, stretchers, and wheelchairs) of the two wards to track their locations. The RFID tags were inexpensive (less than USD 8), and small enough (around 5 cm) so that they could be embedded in the badges of the caregivers and the patients could wear them as wristbands. Figures 3, 4 and 5 showed the RFID tags that were used in the pilot study. In this project, in total, there were 55 patients, 110 caregivers, and 72 equipments tracked in the RFID-enabled environment. All of them were given a unique object ID and registered in the system. In summary, the data captured by this platform were location data about the tagged objects in the wards and have the following characteristics:

- Velocity: In every second, the readers and the tags communicated and the object-location data were stored in the system.
- Volume: The fast data collected from the readers were stored into the system continuously. There were in total more than 15 million records (excluding those records that the location data remained constant in a period of time) captured by the system.
- Veracity: Multiple readers were installed in different locations of the wards to obtain object-location information of high accuracy.

4.2 Major functionalities

4.2.1 Report of person-to-person physical contacts

In the outbreaks of SARS in Hong Kong and MERS in South Korea, by the time these previously unknown deadly diseases had been identified and some patients were tested positive for infection, these patients had already been pathogen carriers for a certain time and had transmitted the viruses to the others (in communities or within health facilities) during the incubation period. In order to effectively and

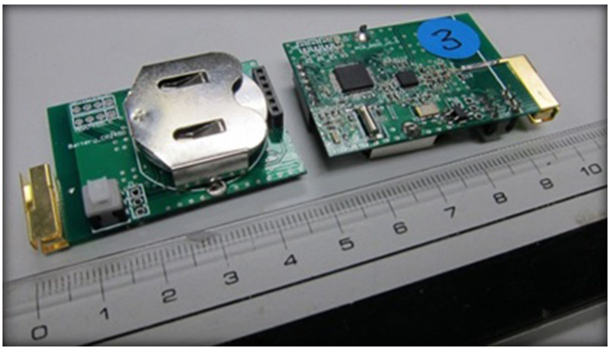

Fig. 3 The front and back of an active RFID tag that was used in the implementation

Fig. 4 The active RFID tags that were embedded in a plastic plate and the plates were placed on the medical equipment

Fig. 5 A patients was wearing a wristband which has an active RFID tag embedded

promptly identify and isolate the high-risk groups of people that had contacted the carrier, a system that can trace the physical contacts associated with this patient will be exceedingly helpful. Our platform is able to report person-to-person physical contacts. A user can define a person-to-person physical contact.The user has to specify how close two individuals were and how long they were together to constitute a physical contact. For example, the user can define a physical contact between two individuals if the two individuals were staying together continuously for 5 s with their distance less than 1 meter. With the user's definition of person-to-person physical contacts, the platform is able to list all pairs of individuals that had contacts. This person-to-person physical contact relationship can be reported using a network diagram, where a node represents an individual and an edge represents a physical contact between them . Figure 6a shows a network diagram which represents the person-to-person physical contacts. The node size and edge size are proportional to the number of individuals that the represented person contacted in the ward and total contact time between them. We can also select a particular person

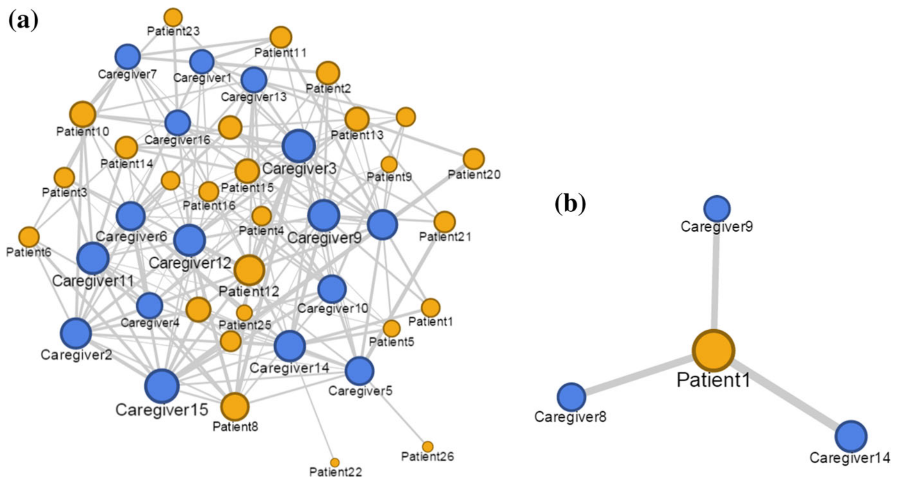

Fig. 6 **a** A graphical illustration of the person-to-person contacts. *Blue nodes* and *yellow nodes* represent respectively the caregivers and patients. The node size is proportional to the total number of individuals that the represented person contacted. An edge represents a person-to-person physical contact where the edge size is proportional to total the contact time. **b** An example to show the individuals that contacted Patient1 (Color figure online)

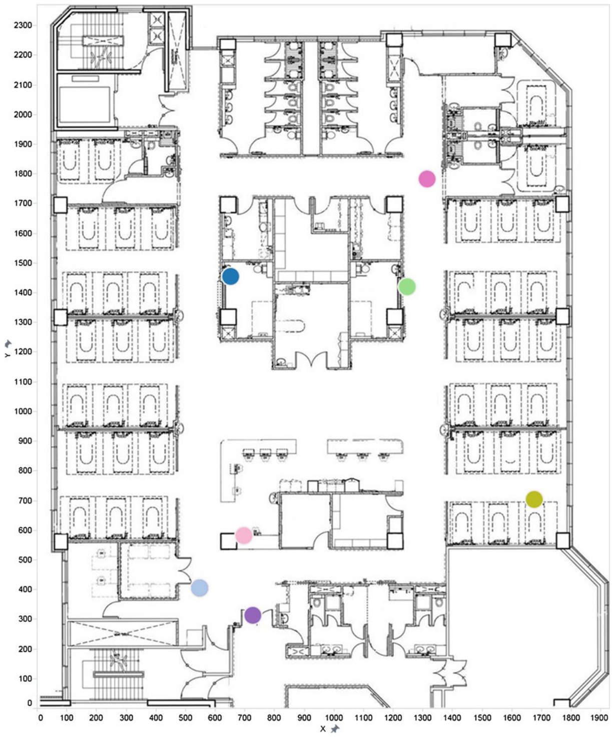

Fig. 7 Real-time visualization of equipment locations. The *different colors* represent different objects (Color figure online)

and identify the individuals that this person has contacted in the incubation period, where an example is illustrated in Fig. 6b. This data visualization technique can enable the hospital management very quickly to trace back whom the patient has contacted physically and identify high-risk contact groups, e.g., the individuals that have a significant duration of physical contacts with the carriers or have contacted a number of carriers. The times and durations that the physical contacts have taken place are also stored in the system for more detailed risk analysis.

4.2.2 Operational support

At an operational level, the platform enables the capability of tracking objects in real time. At any time, the ward staff can easily identify the current locations of patients and medical equipment, as demonstrated in Fig. 7. This practice can save their time in searching for objects and hence can transfer the time to provide extra medical care to patients. The system will also alert the staff if patients are within dangerous areas or tagged objects move out of the monitoring area. This capability not only improves patient safety, but also prevents ward assets being stolen.

4.3 Offline RFID data analytics

This pilot project was conducted between December, 2011 and March, 2012. The real-time location data of tagged objects came to our system almost continuously; during that period, the tags and readers communicated every second. For each tagged object, to reduce the storage required for the large amount of data, we only kept the tracking records that the object moved from one location to another; other records that the object was continuously staying at the same location were all discarded. After removing those records, the total number of tracking records in this period was 15,278,621. Table 1 lists the numbers of tracking records regarding different objects in the two wards. For each observation, the data attributes include a unique observation ID, the timestamp of the observation, the x- and y-coordinates of the object on the floor plan at the time that it was identified by a reader, the reader ID, the object ID, and the object type (i.e., patient, caregiver, or equipment). Due to privacy concerns, in the rest of this paper we present only the data related to the equipment, where those regarding patients' and caregivers' activities are not reported. Excluding those patients' and caregivers' activities, the total number of tracking records regarding the equipment activities was 10,267,260.

Table 1 Number of tracking records in the period of the pilot study

Object type	Ward 1	Ward 2	Total
Patient	113,450	202,500	315,959
Caregiver	1,789,247	2,906,164	4,695,411
Equipment	5,487,907	4,779,353	10,267,260
Total	7,390,604	7,888,017	15,278,621

Fig. 8 Locations of the equipment for a selected day (*at the top*) and for a selected hour (*at the bottom*). The different *colors* represent different objects. The size of a circle is directly proportional to the total time that an equipment spent in the location (Color figure online)

Fig. 9 Paths that the equipment moved for a selected day (*at the top*) and for a selected hour (*at the bottom*). The *different colors* represent different objects (Color figure online)

The stored offline data can be used by hospital administrators to better understand the actual equipment activities, derive insights, and support decision making. Below we demonstrate some of the ways that the administrators can analyze by using data visualization.

4.3.1 Time spent by different objects at different locations

In Fig. 8, we plot the locations of equipment for a selected day (at the top) and for a selected hour (at the bottom). The different colors represent different objects. The size of a circle is directly proportional to the total time that an equipment spent in the location; the larger the circle, the longer time the equipment spent in that location. This helps the hospital management better understand the proportion of time each equipment is spent in each zone on each day and which equipment is frequently used in different zones. Hospital management may consider to add resources to those zones which frequently request some specific equipment. Similar figures can be obtained if we include the data related to caregivers' and patients' activities.

4.3.2 Path tracking for different objects

In Fig. 9, we plot the paths that the equipment moved for a selected day (at the top) and for a selected hour (at the bottom). The platform is also able to calculate the walking distance of an object within a particular time period. When the walking distance is calculated for a ward staff, the ward manager is able to identify the staff

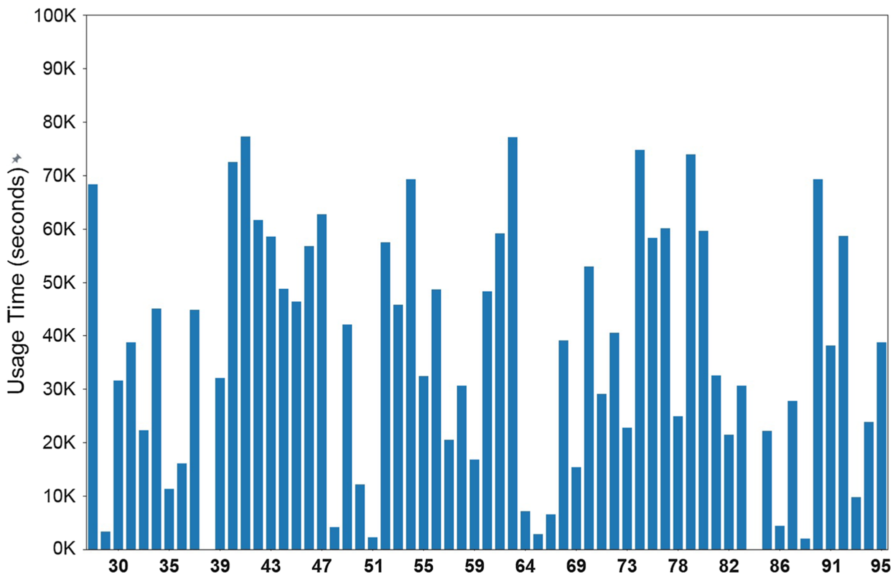

Fig. 10 Usage time (in seconds) of equipment in a selected day

who have moved too frequently and may redesign the workflow. The time-location data about staff can also be associated with those about the equipment and the patients. If a caregiver was with a particular equipment and a patient for a significant time duration, it is very likely that a caregiver was providing the patient with some service using that equipment. Since each equipment is designed for some specific purpose (e.g., an infusion pump is used for injecting medication or nutrients into a patient's body), the concurrence of a caregiver, an equipment, and a patient at the same location point can imply the type of service that the caregiver was providing in that period. This can also help hospital administrators understand the activities of the nurses for better workforce planning and avoiding unbalance workload.

4.3.3 Resource utilization at an item-level

The platform also enables the hospital administrators to understand the equipment utilizations. Using a similar previous argument, we define the usage of an equipment if it has been with a patient for a significant time duration. The platform allows the users to retrieve the durations of which the resources have been busy. Figure 10 shows the total time that the equipment was busy in a selected day at an item level. The data can also be aggregate to visualize the usage of all equipment. Figure 11 shows the total duration that the equipment were being used. The x-axis of Fig. 11 represents the dimension of hour of the day. As an example, we observe that the evening hours, between 17:00 to 18:00, were the peak hours on that day, while the equipment were relatively free between 00:00 and 06:00.

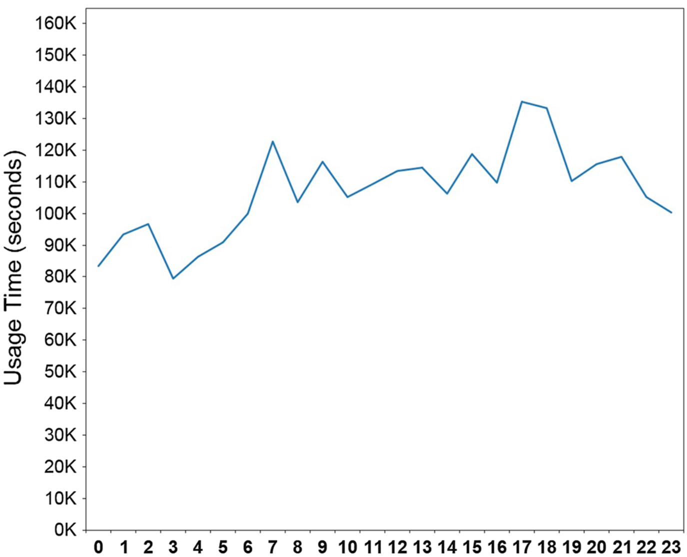

Fig. 11 Usage time (in seconds) of equipment for a selected day

4.4 Main challenges

In this pilot study, the project team also faced some barriers to implement this RFID-enabled platform. These barriers are not technological challenges, but the patients' resistance to wearing a RFID tagged wristband during the their length of stay. Out of the 182 patients who were referred by the ward staff to participate this pilot study, 127 declined. There were physical obstacles that the patients were not able to participate. For example, it was not recommended because patients' both wrists were full of needle applications or due to their skin conditions. Besides patient physical conditions, some of the patients were reluctant to participate due to various personal reasons, e.g., resistance to advanced technology and unwillingness to being tracked during the length of stay. This indicates that there are still human issues to be resolved prior to the adoption and implementation of RFID technology to track patients, which are beyond the technical challenges that researchers and engineers are able to handle.

5 Conclusions

In the era of big data, healthcare units are able to capture, process, manage, and utilize big data to generate extra values to benefit the healthcare stakeholders. Although there have been various applications of big data for healthcare use, the healthcare industry is still lagging behind other industries such as retail and banking. This indicates that there is a need to further promote big data in the healthcare domain. In this paper, we presented an active RFID-enabled platform to keep track of the locations of patients, ward staff, and medical equipment, for hospital ward management. The platform empowers real-time monitoring and tracking of objects, reporting of ward statistics, and providing intelligence and analytics. A distinctive feature of our proposed platform is that, all the individuals, including ward staff, are tagged and their locations are tracked continuously. This enables the traceability of person-to-person physical contacts in case of an infectious disease outbreak so as to provide immediate and effective response to mitigate risk of disease widespread within the hospital. A pilot study which deployed a prototype developed based on our proposed architecture of the platform was conducted in two medical wards of the intensive care unit of one of the largest public general hospitals in Hong Kong. Although the pilot study demonstrated its feasibility for practical use, we also report some of the human issues that obstruct its adoption and implementation, which are beyond the technical challenges that researchers and engineers can handle. Furthermore, installation of a RFID-network can be costly due to the infrastructure (e.g., active RFID readers, wiring, and some construction work) and the development of a middleware so that hospital management may hesitate to adopt the technology. Nevertheless, these costs are mostly one-time initial set-up costs, because the tagged wristbands can be reused, while the maintenance cost is relatively lower. The hospital also further benefits from cost saving by preventing valuable medical equipment being stolen [e.g., the price of a cardiac monitor ranges from a hundred to several thousand US dollars according to Alibaba.com (2015)] and well-utilizing the scarce medical staff, who have been in huge shortage in the medical system particularly in Hong Kong (Chinadaily Asia 2014). We also believe that the implementation of this RFID-enabled platform would benefit the healthcare stakeholders by the advantages of enhanced patient safety, increased operational efficiency and throughput, and mitigation of infectious disease widespread. Most importantly, the enhancement in effectiveness and efficiency of medical service delivery to patients and the capability of mitigating patient risk can improve patient health outcomes and even save more invaluable human lives that can hardly be measured in monetary value.

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