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Enabling RFID technology for healthcare: application, architecture, and challenges

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Abstract Information processing is the cornerstone of patient safety and healthcare quality. In the current healthcare system, critical gaps exist in the collection of vital information from patients and transferring that information to healthcare providers. The information collection problems are particularly challenged in patients lacking verbal communication or under other serious conditions. Information handover among medical staff can also introduce human errors which may place a patient's health and life at risk. Radio frequency identification (RFID) is a kind of electronic identification technology that is becoming widely deployed. RFID technology allows crucial personal information to be saved in a low-cost chip attached to the patient. This innovative technology has tremendous potential to improve patient healthcare quality by eliminating human errors and ambiguity presented during patient-physician and physician-physician interactions.

Keywords Healthcare · RFID · Electronic Medical Records

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1 Introduction

Aging population and sedentary lifestyle are fueling the prevalence of chronic diseases such as cardiovascular diseases, hypertension and diabetes. According to the World Health Organization's statistics, millions of people suffer from obesity or chronic diseases every day.

Patients are brought to hospitals with various health problems. The most critical health problems may deprive the patient of the ability for verbal communication. Each year in Canada, about 9,000 new brain stroke (blockage in arteries that supplies blood to certain areas of the brain or the rupture of these blood vessels) cases are consulted by physicians at acute care clinics nation-wide. Providing treatment within the first 3 h after the onset of stroke symptoms is highly emphasized within the new Canadian Best Practices Recommendations for Stroke Care guideline issued by the Canadian Stoke Strategy [1]. Generally, people suffering from a stroke often fail to communicate clearly with medical staff during the hospital visit as verbal communication disruptions are the second most common stoke syndrome. As a result, the difficulty in collecting reliable information from patients often leads to treatment delivery at times beyond the critical phase [1,2]. Furthermore, approximately 1.9 million Canadians were diagnosed with diabetes in 2005–2006. In diabetic-associated hospital visits, one third of patient treatments are delayed due to the difficulty in identifying patients' illness history and medication history [3]. The situation is

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even worse when patients are under the attack of coma, either caused by sudden change of sugar level (hypoglycemic and hyperosmolar coma) or build-up of toxic chemicals (ketoacidotic coma) in the blood stream. Moreover, there is a high prevalence of diabetes within the senior population (23 % in 75–79 age group) [4]. This compounds diabetic-related communication disabilities when combined with the fact that the senior population is also at a high risk of developing mental problems such as dementia (severe impairment or loss of intellectual capacity and personality integration, due to the loss of or damage to neurons in the brain) [5]. The leading cause of dementia in Canada is Alzheimer's disease, which has reported prevalence rates of 5.1 and 21 % in population groups over the age of 65 and 85 years respectively [6]. Interruptions in the communication ability of young Canadians can be due to trauma as unintentional injuries are the leading cause of death in Canadians under the age of 45. Physical and mental shocks caused by a trauma, such as motor vehicle crashes, drowning, falls, poisoning and burns will lead to the temporary memory loss of victims and lack of communication abilities. In lucky cases where patients can still make conversation with medical staff, information provided by them is often vague and incoherent [7]. Failure to identify allergies to medications is another area in which miscommunications can be fatal. Approximately 2–3 % of hospitalized children in Canada are allergic to penicillins, a prominent class of antibiotics [8]. Among these penicillin-allergic patients, 1 % have hypersensitive reactions and as such even a miniature dose of penicillin used for skin test can claim the life of the patient. Thus, it is crucial for a penicillin-allergic patient to advise a healthcare provider about his/her allergy history [9]. However, this process is often unsuccessful in the real world. Reliable and low-cost solutions are urgently needed to save and report patients' medication and allergy histories during their hospital visits.

With the rapid advances in electronics, electromechanics, and nanotechnologies, radio frequency identification (RFID) technology has opened up new frontiers in the race to conquer the information collection problems in healthcare. A tiny embedded RFID tag can "tell" the backend system accurately to shorten the critical gaps that currently exist during the collection and subsequent handover of the vital patient information. The RFID tag can hold and transmit hundreds of bits of information with a simple transmit chip and an antenna. The identification information can be saved in an RFID tag which can be attached to an object. Information can be read with a radio frequency reader. RFID has been used in the healthcare field to improve the effectiveness of operating room and tracking blood samples [10,11]. The impact of applying RFID technology to healthcare applications in order to improve patient care is appealing.

In this article, we explore how RFID technology can be deployed for electronic Health (eHealth) systems and we provide an overview of the various issues that arise with the use of such a technology.

The rest of the paper is organized as follows. Section 2 briefly describes RFID technology. Section 3 discusses how RFID technology can support healthcare environments through our proposed RFID infrastructure and Sect. 4 evaluates its impact on a patient's life cycle. Section 5 overviews some typical RFID-enabled healthcare applications. Section 6 discusses various challenges and open issues that must be addressed to leverage RFID support in healthcare applications. Finally, Sect. 7 provides some concluding remarks.

2 RFID technology

Radio frequency identification (RFID) [12] is a radio-frequency (RF) electronic technology that allows automatic identification or locating of objects, people, and animals in a wide variety of deployment settings. In the past decade, RFID systems have been incorporated into a wide range of industrial and commercial systems including: manufacturing and logistics, retail, item tracking and tracing, inventory monitoring, asset management, anti-theft, electronic payment, anti-tampering, transport ticketing, supply-chain management, etc [13].

A typical RFID system consists of an RFID tag, an RFID reader, and a backend system. With a simple RF chip and an antenna, an RFID tag can store information that identifies the object to which it is attached. There are three types of RFID tags, i.e., passive tags, active tags, and semi-active tags. A passive tag obtains energy through RF signals from an RFID reader, while an active tag is powered by an embedded battery, which enables larger memory or more functionalities. Though a semi-active tag communicates with RFID readers like a passive tag, additional modules can be supported through an internal battery. When the semi-active tag comes within the proximity of a RFID reader, the information stored in the tag is transferred to the reader, and onto a backend system, which can be a computer employed for processing this information and controlling the operation of other sub-system(s).

RFID technology has tremendous potential in improving healthcare delivery in both hospital and home environments. In RFID-based eHealth systems, RFID enables remote identification and tracking of patients, staffs, drugs, and equipment. It could speed up or eliminate many manual operations and increase safety by, for example, tracking drugs along the supply chain and verifying their compliance with patient's medical history. Moreover, RFID-integrated systems would be able to optimize workflow, and provide support for dynamically managing personnel, equipment and medicines stock.

3 Architecture of an RFID-based healthcare monitoring system

3.1 Overview

In this section, we describe the architecture of an RFID based healthcare monitoring system. As shown in Fig. 1, we decompose the functionalities of the system architecture into four components, namely tagged objects, RFID information capture and delivery system, the patient-aware contexts querying system, and the medical information central system. This architecture facilitates the creation of a component-based and efficient RFID- based healthcare management system for a wide range of applications. The design goals of each component make it possible to support specific requirements (e.g., cost, coverage, efficiency, etc.) of application contexts [14] and market demands.

3.2 Tagged object as information source

There are four main objects in healthcare environments: (i) *Patient*: patients wear a smart tag storing their identifier; (ii) *Medical equipment*; (iii) *Physician and nurse*: medical staff often has to manage more complex medicines, medical techniques and equipment. A tagged Personal Digital Assistant (PDA) which they use to access the hospital's applications through a wireless network. (iv) *Medicine*: Drug packages are tagged by the manufacturer, and those tags are integrated into the hospital's RFID system.

Objects are embedded with RFID tags to facilitate the information handover. Basically, there are four pieces of information: (i) the object's identification; (ii) electronic medical record (EMR) for the patient; (iii) description information for medical equipment (e.g., type, color, shape and weight, etc.); and (iv) directive (stored in the tag for medicine) that guides the patient to take medicine correctly.

Accurate and timely information collection is important for physicians to provide prompt and appropriate treatment for patients. Incomplete information or delay of information collection can cause medical errors and fatal consequences at the cost of patients. When patients arrive at healthcare facilities, healthcare providers are trained to obtain comprehensive medical information from patients. However, for instance, in the Canadian health system, critical gaps still exist between information collection and patient's expectation on healthcare services. The situations become even more critical in cases when patients visit a hospital with inadequate verbal communication ability or for emergency healthcare [15]. Subsequently, the transfer of medical information among medical staff can also introduce human errors which may put a patient's health and life at risk [16,17]. Several educational initiatives which emphasize improving communication skills of physicians have been employed to close the critical communication gaps [18,19]. However, to date the outcomes of these initiatives have been inconsistent, due largely to the fallible nature of human operator in the extremely demanding, complex, and dynamic situations such as in the emergency rooms of a hospital [18,19]. In the proposed architecture depicted in Fig. 1, we leverage RFID technology to the healthcare environment with the primary goal of minimizing the information gap in the patient care process. The unique features of RFID allow crucial personal information to be saved in a low-cost chip that can be attached to an individual at all times. When the RFID-attached individual visits a hospital for health problems, information saved in the RFID chip can be read by medical staff with a radio frequency reader. This innovative technology has the potential to improve patient care quality by eliminating human errors and ambiguity presented in patient-physician and physician-physician interactions [20].

3.3 RFID information capture and delivery

RFID information can be captured in an *active* mode or a *passive* mode:

- *Active mode:* In this mode, the reader is mobile. For example, doctors, nurses and other staff members have a handheld device (PDA, mobile phone, laptop, etc.) equipped with a reader and a wireless connection. These people holding the RFID reader-enabled equipments retrieve the patients' information actively when they is close to them.
- *Passive mode:* In this mode, the reader is fixed. Readers are placed in rooms, operating theaters, and corridors in order to read tags that pass through these places. Some items (for example, beds) of the medical equipment can carry an RFID reader.

Once the information is captured from the tagged objects, readers send the captured data through an access point (that can be positioned on the wall) via a wired or wireless network to the medical information central system, as shown in Fig. 1.

3.4 Medical information central system

The Medical information central system consists of a medical information database and an inference engine.

The database maintains patients' profile and medical history. According to a patient's service priority and/or doctor's availability, the doctor may access the patient's information as needed. At the same time, automated notifications can be issued to his/her relatives based on this data via various means of telecommunications.

An inference engine usually corresponds to a kind of knowledge representation [21]. Similar to an inference engine with a traditional rule representation, the inference engine with the tree-structured knowledge base performs a query and outputs a solution to the query. The query takes several situation sentences in a situation vector as input, which describes a situation in the specified context, and outputs a solution as a result of the query.

The inference engine can be implemented as a middleware which is a key component of RFID systems. The primary goal of such a middleware is to hide the management complexity of RFIDs and support their integration within background business systems. It manages readers, supports mechanisms to add and remove them, to filter and aggregate data, and to define security policies such as access control. The middleware also interprets the data in to input to the business systems through a shared interface.

Considering the potentially huge quantity of tags and readers that make up a hospital's RFID system, the middleware has to be dynamic, extendable, and reconfigurable and has to guarantee the interoperability with other software. The EPC Global Specification, being the first to appear, has been largely adopted. It enables the definition of very large structures for extremely complex application scenarios. However, this characteristic also leads to inconvenience because of its lack of flexibility and customization, particularly in light deployment environments. Consequently, industry and academia are working on novel RFID middleware architectures that can fully satisfy the requirements. Their efforts are mostly service-oriented platforms built over the Open Service Gateway Initiative (OSGi) platform, which is a framework for deployment and execution of Java-based applications. Indeed, the strengths the OSGi specification include its modularity, extensibility, the ability to add/remove modules dynamically, configurability, and ease of remote administration.

3.5 Patient-aware contexts querying system

Context information such as identities and locations provided by RFIDs could also be incorporated within wireless multimedia networks or body area networks to support ambient intelligent services for patient care.

The patient-aware contexts querying module is used to retrieve environmental parameters that enable the medical information central system to make a decision. As shown in Fig. 1, the typical patient-aware contexts querying system can include wireless body area networks [22], wireless sensor networks [23–26], video surveillance system [27], and positioning system, etc.

3.5.1 Wireless sensor networks

Advances in low-power wireless technologies and MEMS (Micro Electromechanical System) allow the retrieval of context-aware information in an ambient intelligent environment consisting of wireless sensor networks. An ambient intelligent environment consists of a multitude of interconnected embedded systems which are embedded with computational and networking capabilities which form a ubiquitous, unobtrusive and seamless infrastructure to collect the surrounding context of a user. Context-aware information can be characterized by the situation of an entity, which can be a person, a place, or a computational or media object that is considered to be relevant to the interaction between a user and an application. For example, in order to get the environmental temperature and humidity, a notification is sent to the sensor nodes in the region of interest to sense the environment.

3.5.2 Positioning system

The location of the RFID reader, where an object is recognized, can be considered the coarse location of the object. If more accurate location information is required, an exclusive positioning system needs to be deployed. The realization of a fine-grained or coarse-grained positioning system is a tradeoff among accuracy, system complexity, and cost. To realize a fine-grained positioning system, various localization algorithms can be exploited in wireless sensor networks (WSNs), facilitating a physical object to estimate its own position. The localization algorithms can be divided into range-based, angle-based, and range-free approaches. Although both range-based and angle-based approaches provide a lower estimation error than the range-free approach, they require specialized hardware for sensor nodes to obtain relatively accurate measurements. This may not be cost effective for applications that require hundreds of sensor nodes over a large coverage area. An important research issue is to improve distributed range-free algorithms with higher accuracy and low implementation complexity.

3.5.3 Wireless body area networks

The advent of miniaturized sensors and actuators for monitoring, diagnostic and therapeutic functions along with advances in wireless technology have opened up new frontiers in the race to conquer healthcare challenges. The ultra-low-power wireless connectivity among the devices placed in, on and around the human body is seen as a key technology enabling unprecedented portability for monitoring physiological signs in the hospital, at home, and on the move.

In the particular case of E-healthcare systems, physiological signals (e.g., body temperature, blood pressure, heart rate, etc.) convey useful health condition information of a person who needs to be remotely monitored on a constant basis by a qualified healthcare practitioner. These signals are obtained by means of tiny sensors attached to his/her body (arms, legs, etc.) to form a WBAN. In addition, ultra-low power Zigbee technology (also known as IEEE 802.15.4) is particularly suitable for linking sensor and other types of devices with a WBAN to support external communications (as we explain shortly) [28]. Ultimately, the data collected by a WBAN can be readily examined at a healthcare facility to ensure that the patient receives the appropriate treatment as needed.

Sensors such as ECG (Electromyography), EEG (electrodes), EKG (Electrocardiogram), EMG (Electroencephalography), motion sensors, and blood pressure sensors send data to nearby personal server for data aggregation and processing, which can be a cell phone, watch, headset, PDA, laptop, or robot, based on the application needs. Then, through Bluetooth/WiFi, such data are streamed remotely to the doctor's side for real time diagnosis, or to medical database for record keeping, or to request for emergency services.

3.5.4 Video monitoring

While self-configured multi-hop Wireless Sensor Networks (WSN) have been widely studied, the use of WSN for video surveillance is more challenging and merits more in-depth research and development. The overall goal of the proposed architecture is to address the design issues of WSN-based Video Monitoring Systems from a complete system perspective, taking into account the generation, transmissions, storage, retrieval and consumption of video information.

If necessary, doctors or other caregivers can communicate with patients directly through video conferencing via the Internet. In fact, it might be possible for the doctor to remotely diagnose a problem by relying on both video communications with the patient and the patient's physiological data information retrieved by a wireless body area network hosted by the patient. However, there are several challenging issues that need to be addressed for the deployment of a light-weight video monitoring system including: (i) algorithms for multi-camera video capture, efficient multi-resolution coding, feature identification, and data fusion/reduction, (ii) methods for efficient high quality video transfer over bandwidth and power constrained multi-hop wireless networks, and (iii) mechanisms for efficient video data storage and retrieval.

4 System operation during the patient life cycle

How RFID can be applied to improve healthcare related operations or surgical operations can be understood from the perspective of a patient's treatment life cycle in the hospital. Many hospitals track their patients using manual systems. Typically these are paper-driven, utilizing everything from whiteboards, cards, and charts to self-adhesive notes. Generally, the patient treatment ife cycle has six stages:

- *Admission:* The first step in admission to a hospital usually involves paperwork filled out by both patient and hospital staff. Recorded information includes the insurer/ability to pay, patient name/contact data, and the reason for admission. Next, the patient is assigned an ID number that is written on a chart and on a wristband attached to the patient.
- *Examination:* Once formally admitted, the patient is taken to the department handling diagnostics and treatment. At each treatment step, the wristband and charts (including medical orders) are visually inspected to confirm that the right patient is being treated. Such checks utilizing RFID to assure the correct patient is being treated can be applied to all other procedures, as well as to patient transportation within the hospital and, ultimately, to discharge from the hospital. Errors are a major problem with today's medical care. But RFID technology can be applied to address many potential errors, including: (i) contraindicated medications - by using the RFID database to track a patient's medications and to raise a red flag when they present problems; (ii) matching medications to the right patient by matching the name on the medical orders to the name on the patient's wristband; (iii) matching specimen collection to the right patient - by coding the patient's name in the tag on the specimen bottle. When first treated, the patient is questioned about his or her problem, and examined visually. If this does not provide the cause of the illness, tests are performed to determine possible causes. Still more tests may be necessary, and once enough information is obtained treatment either begins or the patient is discharged.
- *Patient care:* If further care is needed, the patient is assigned a bed and transported to a room. At regular intervals, the following procedures could be carried out: (i) blood is drawn (by a phlebotomist) and analyzed; (ii) blood pressure, heart rate, temperature, and O_2 saturation are recorded; (iii) intravenous (IV) fluid levels are recorded and replaced as needed; (iv) other evaluations of the patient are recorded (for example, pupil condition, motor skills, awareness, pain sensations); and (v) other specimens are obtained and sent to the laboratories. During the course of care, the patient may be transported to other departments for treatments, tests and examinations. To document what being done, the caregivers record each and every action and the results on the patient's chart, as shown in Figs. 1 and 2. The information flow during the operation of patient care is presented in Fig. 3.

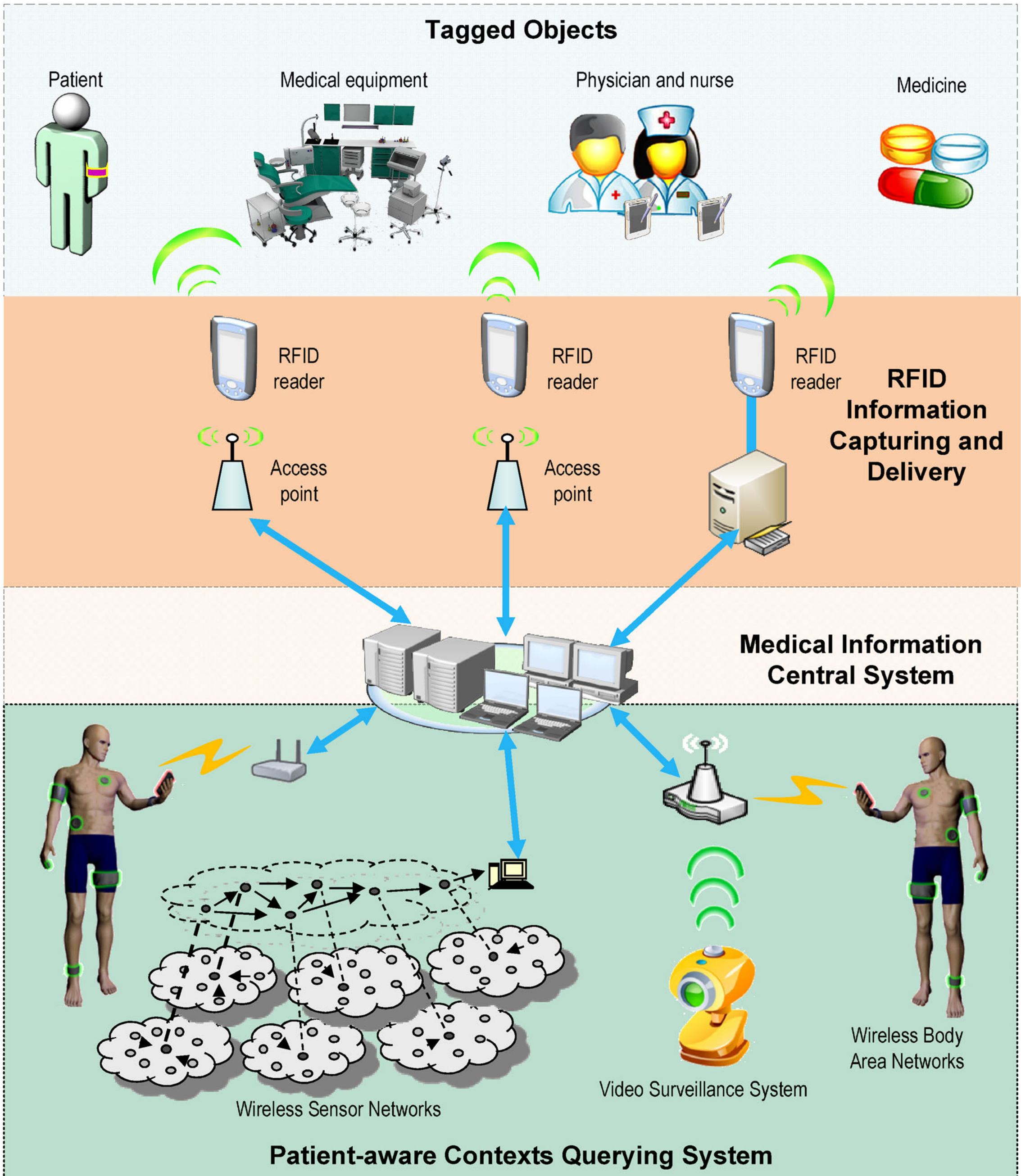

Fig. 1 Architecture of RFID based healthcare system

– *Recovery:* As the patient improves, he or she is encouraged to walk for exercise. These movements are recorded (that is, when the patient left and returned). Meals, medical supplies, and medications consumed by the patient are also recorded.
– *Discharge:* When the physician determines that hospital care is complete, the patient is issued post-hospital care instructions, and processed for discharge. Leaving the hospital, the patient is typically moved in a wheelchair to the curbside or taken home using a non-emergency medical transport service.
– *Billing:* Billing information is processed and statements sent to various parties (for example, to the insurer) for payment [29].

5 Application overview

In this section, we overview some typical applications and projects using RFID technology to develop advanced E-healthcare systems. In indoor wayfinding project [30], the passive RFID tags are deployed once and addition of new

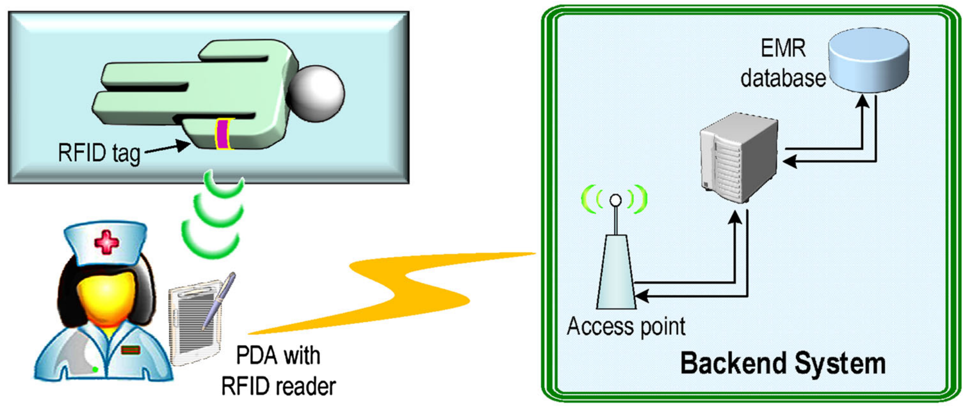

Fig. 2 The illustration of nurse's operation during patient care

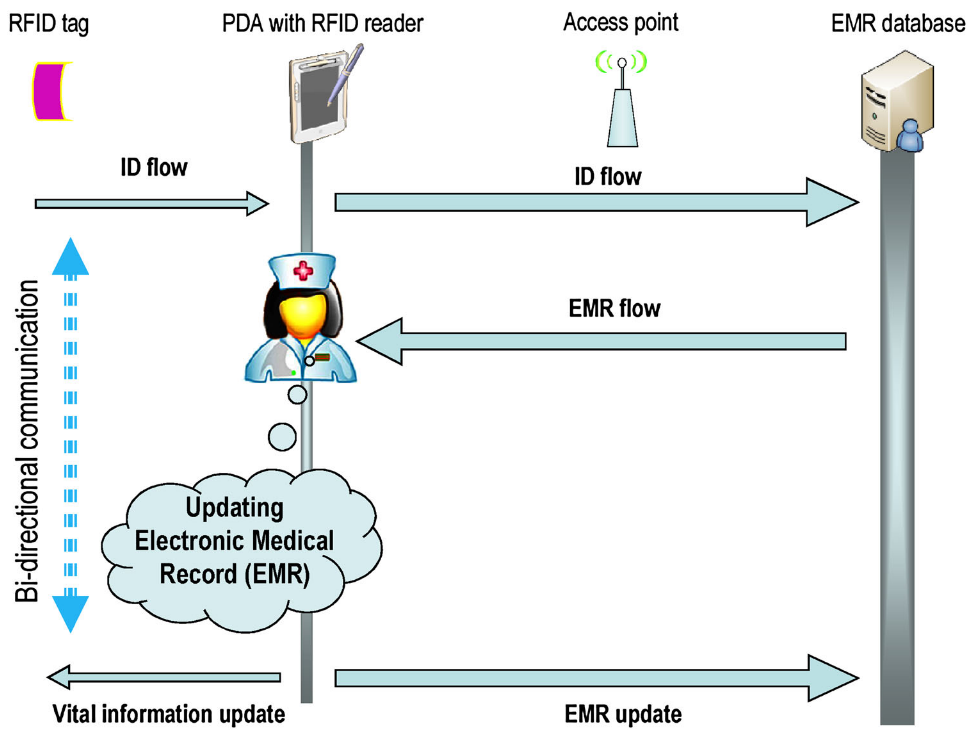

Fig. 3 The information flow during the operation of patient care

patients does not lead to a change in the configuration. In Caregiver' Assistant [31], inexpensive RFID tags are placed on household object and the systems precision can be increased at very low costs, by tagging more objects with inexpensive RFID tags. In UltraBadge [32], WISP [33], and mPCA [34], small RFID and ultrasonic tags or video sensor nodes are utilized to make healthcare applications unobtrusive. In [35], a new E-healthcare system (2G-RFID-EHS) based on the 2nd generation of RFID technology is proposed with the distinctive feature of the installation of a mobile code (including patient identification and dynamic medical information) to RFID tags rather than having it saved in a profile database [36]. This new approach effectively relieves the dependency of a RFID tag on information querying from a database.

5.1 RFID applications for patients care

The prototype described in [37] aims to control the medicine intake of the elderly with the combined use of sensor networks and RFID. It consists of three subsystems. The Medicine Monitoring Subsystem is used for medicine bottle identification using high frequency (HF) RFID tags and the amount of the medicine removed by the user is tracked by a weight scale. The system is able to determine when and which bottle is removed or replaced by the patient and the amount of medicine taken. The patient wearing an ultra high frequency (UHF) RFID tag is identified and located by the Patient Monitoring Subsystem and the system is able to alert the patient to take the necessary medicines. Finally, the Base Station Subsystem is responsible for message relay to the

Base Station personal computer (PC). The Base Station software is responsible for (i) simulating a display and its GUI for the patient; (ii) determining when medicine is required; and (iii) maintaining various interactions between the Medicine Mote and the Patient Mote.

The iCabiNET [38] solution makes use of the smart RFID packaging that can record the removal of a pill simply by breaking an electric flow into the RFID tag's integrated circuit. iCabiNET is an indoor application that is also interfaced to a residential network, in this way, the medicine intake can be monitored over the residential network by using the RFID readers at home. The system is capable of monitoring the drugs that are bought by the user and when the presence at home is detected the smart appliances, such as TV, can be used to inform the patient about the usage and dosage. Furthermore, an interactive TV application can also be integrated with the system that allows the purchase of the new packet of the drugs when the supply is decreased. As an alternative scenario, the iCabiNET system can be integrated with the cellular network or ordinary telephone network in order to remind the patients to take their medication correctly.

The Wireless Identification and Sensing Project (WISP) [33] explore the enhancement of passive RFID tags with sensors so that tags can also send sensor data to the readers. The tags capable of sensing are called wisps. The prototype design that is capable of sending one-bit accelerometer data is called the α-wisp. It uses ID modulation and by using a mercury switch it can communicate two different ID for two different inertial situations, therefore it is battery-free. In an ADL recognition prototype, several household objects are tagged with α-wisps and RFID antennas are placed in room corners. The prototype requires about a thousand of objects to be tagged although typically less than 10 objects are actively used at any time.

The Caregiver's Assistant [31] is designed to monitor the elderly in their home environment. Basically, the system works by outfitting various items throughout the user's home with RFID tags (e.g., medicine bottles, toothbrushes, keys, etc.). These tags along with a tag on the user's hand make up wireless sensor networks that enable real-time monitoring of which items she is picking up. Time stamps, duration and patterns of use are extrapolated from this data and are compared to a baseline. All of this information is recorded automatically on electronic daily activity forms and presented in an application with graphs and charts. Thus, healthcare professionals are able to monitor any deviations from the elderly user's normal activities. The sensor networks are established throughout the user's home. When the user picks up an item, the tag on the item and the tag on the user communicate. The data is transmitted to a reader within the user's home. This could be a personal computer that has a connection to the Internet. The data is then transmitted via RFID to the reader, over the Internet to the healthcare professional who monitors the data streaming in. The raw data coming into the system is translated via an activity tracking system that uses dynamic Bayesian networks and artificial intelligence technology to meaningful trending information about what activities people are doing at home.

In [30], an RFID based way finding system for cognitively impaired patients is presented. Passive RFID tags are placed in important locations where patients need to make decisions about the next action to take, such as turning right or left. Patients carry PDAs that have built-in RFID readers to identify the location by reading passive RFID tags and provide just-in-time directions to guide the patients to the destination also providing with spatial photos. A tracking function is present where the visited positions are tracked and logged and in case of anomalies, alarms are raised.

The work presented in [39] combines the data from RFID readers and accelerometers in order to classify the activities of daily living. Classifying activities of daily living by using only RFID technology requires a large number of RFID tags to be placed on the objects. Likewise, by using only accelerometers, there should be several sensors placed on body locations such as wrist, hip, and thigh. In this work, a single 3-axes accelerometer worn on the wrist is used and reducing the number of RFID tags did not affect the results significantly.

5.2 2G-RFID based E-healthcare system

In [35], Chen et al. [35] address the passive features in current RFID systems (called first-generation RFID systems (1G-RFID-Sys)) and indicate the difficulties in adapting such systems to meet application-specific requirements. They propose second-generation RFID systems (2G-RFID-Sys) in which encoded rules are dynamically stored in RFID tags. A novel E-healthcare management system based on 2G-RFID-Sys is demonstrated with improved system scalability, information availability, automated monitoring and processing of sensitive information, and access control.

In a 2G-RFID-Sys based E-healthcare system, the medical conditions of a patient can be monitored as required by the corresponding healthcare system, and subsequently updated into the database by means of a cell phone, a Wi-Fi connection, etc., depending on the patient's location. Any abnormalities that do not require immediate treatment may be logged into the database, and registered by the patient's RFID tag for future reference. If necessary, doctors or other caregivers can communicate with patients directly by video conferencing via the Internet. In fact, it might be possible for the doctor to remotely diagnose a problem by relying on both video communications with the patient and the patient's physiological data information retrieved by a wireless body area network hosted by the patient. If needed, the patient can then be asked to visit the healthcare facility. When the doctor arrives, the doctor uses his/her RFID reader to read the information from the patient's RFID tag, such as recent medical history and pharmaceutical history. Then, the doctor writes diagnosis information, medical methods and prescription information into the mobile code of the patient's RFID tag after current operation for the patient, which will improve patient care quality by eliminating human errors and ambiguity presented in patient-physician and physician-physician interactions.

2G-RFID-Sys finds its unique effectiveness particularly in information collection and transformation when handling medical emergencies. For example, an ambulatory patient travelling to a location outside his/her home town might experience a critical situation due to a medical condition that requires immediate attention. Using an 1G-RFID-Sys here would imply that emergency medics could read the patient's ID embedded in the tag, and attempt to remotely retrieve the patient's medical history from his/her home hospital. The 1G-RFID-Sys has the shortcoming that, if the corresponding database is unavailable or if the necessary security clearances and/or data access protocols have not been pre-established, then the patient might not be aptly treated according to his/her existing medical conditions (which other doctors might be unaware of), especially for a patient who is unable to verbally communicate with healthcare providers.

6 Open research issues

RFID is a promising technology that, if efficiently implemented in healthcare environments, will result in numerous benefits to all including physicians, healthcare providers, patients, and several other parties involved in the delivery and administration of healthcare services. However, several challenges still remain that must be addressed before RFID technology can be ubiquitously deployed in healthcare environments, applications, and services. In the following section, we highlight some of these challenges open issues that still need further investigation.

6.1 Interference

The ElectroMagnetic interference (EMI) caused to the electronic biomedical devices by RFID wireless transmissions could critically affect the performances of these biomedical devices.

Without careful investigations of the impact of such interferences, the introduction of RFID into medical environments might threaten patient's safety. Indeed, the electromagnetic interference generated by RFID tags and readers can potentially disrupt the performance of electronic medical equipments [40]. A syringe pump or an external pacemaker that switches off in the proximity of RFID devices would directly endanger a patients' health. Depending on their frequency band, passive tags, which have a higher energy output, can induce more disruptions than active tags. On the other hand, their read range being much shorter, they minimize spatial interference. In some cases, the electromagnetic interference is due to different modulation rates rather than the carrier frequency or the emitted energy. In addition to updating safety standards for electronic medical equipments, power control mechanisms depending on RFID density and frequency bands should be considered as a solution to minimize the impact of electromagnetic interference.

6.2 Security and privacy

The main challenging issue in RFID information delivery is to guarantee security and privacy. For example, a malicious person could write code illegally that can impersonate the identity of a patient [41].

RFID tags, by default, communicate with all surrounding devices, both good and malicious. RFID privacy relates to misbehaving readers harvesting information from well-behaved RFID tags. Since RFID tags automatically respond to the interrogation from the reader without alerting the bearer/owner, a person carrying an RFID tag is prone to clandestine physical tracking. In addition, in supply chain applications, individually tagged objects in stores allow competitors to learn about the stock turnover rates (often referred to as inventorying).

The highly limited computational capabilities of an RFID tag make it a challenging environment for designing and implementing security functions. While such tags might typically have a few thousand gates, any future advances in chip design will likely be used to diminish the cost of tags rather than to increase computational capability. Thus the issue of limited computational resources still needs further investigation to develop novel solutions that can implement highly efficient, secure solutions. In particular, traditional security solutions using public key cryptographic primitives such as digital signatures, secure key exchange, key distribution systems and others are not optimal solutions. In such a limited environment, it is important to have a clear and precise assessment of the security attacks that can be addressed.

Following the treatment in [42], RFID tags can be classified according to their computational capabilities which make them a challenging environment for designing and implementing security functions. As mentioned earlier, while such tags might typically have a few thousand gates, any future advances in chip design are likely to focus on diminishing the cost of tags rather than increase their computational capabilities. As a result, the issue of limited processing capability is likely to persist in the future. At the next level of RFID ability one might assume a number of gates in the order of a thousand or slightly more. This might allow a simple hash function and a lightweight encryption system. In turn this would allow more sophisticated security notions such as authentication and a greater level of privacy to be considered. It will also require notions of key distribution to be addressed. Even for these functionalities, minimalist implementations will have to be carefully researched. For privacy protection, we need to investigate techniques such as periodic re-encryption, monitoring devices for privacy enforcement, dynamic blocking approaches, and symmetric-key function. For authentication mechanisms of semi-active and active tags, we need to consider the use of symmetric-key functions and other encryption techniques with optimal computation costs. Different key distribution techniques also need to be considered.

6.3 Authentication mechanisms

Efficient authentication algorithm is needed to ensure the security of smart RFID systems but the privacy issue is also important. For example, another malicious person may activate the RFID tag attached to a patient, access the electronic medical record, and do something adverse to him/her. Thus, the code should only be delivered to trusted RFID readers.

RFID authentication focuses on the problem of well-behaved readers harvesting information from misbehaving tags (e.g., counterfeit ones). Basic RFID tags (e.g., Electronic Product Code (EPC) tags of Class-1 Gen-2 type) are vulnerable to simple counterfeiting attacks. An attacker can skim the EPC from a target tag and then program it into another counterfeit tag. RFID tags are also prone to relay or man-in-the-middle attacks. Since RFID tags have a small amount of storage and processing capabilities, innovative and efficient RFID authentication techniques are needed.

6.4 Data/decision fusion algorithm

Another critical factor in RFID, which is closely related to the radio frequency operating range, is read-accuracy (also referred as detection reliability); that is, the probability that a tag is successfully detected by a reader. Previous research in this area has mainly addressed the read accuracy problem by considering a single reader, whose read-accuracy is mainly determined by the read range of this reader. However, it is envisaged for various applications that readers will become more densely deployed and form a network of readers that performs the task of tag reading in a collaborative fashion. Then, assuming that various copies of the tag signal or processed versions of it are available at a centralized network node (such as a gateway), efficient data fusion algorithms can be utilized to improve radio frequency tag detection reliability and operating range. In a distributed system set-up, efficient decision schemes need to be developed. One promising way is to exploit cooperation strategies between readers.

6.5 Tracking of mobile tags

Tracking (or object tracking application) refers to the operation of monitoring the location of the tags by a central system. Indoor tracking requires the use of either infrared, ultrasound, radio frequency technology, or a combination of these techniques. Each technique has its own strengths and weaknesses with respect to accuracy, flexibility, and costs. An infrared-based solution requires line-of-sight for object identification. Ultrasound is relatively accurate but may not be suitable for tracking a large number of objects simultaneously. The active RFID tracking prototype in [43] requires signal strength information from each tag to the readers. Information collected from various readers is then sent to the centralized server which invokes a lateration algorithm to estimate the position of the tags. The accuracy can be further increased by using stationing reference tags. Other RF-based techniques use the signal strength measurement from a wireless local area network (WLAN) [44] as in the RADAR system [45]. For applications which require the reader to estimate the tags within its range, an anonymous tracking algorithm has been proposed [46].

6.6 Reader collision problem

Packet collisions can also occur when multiple co-located RFID readers transmit signals simultaneously to an RFID tag. Such reader collision should be minimized in order to ensure the operation of the system. One option is to let each reader operate on different frequencies. However, FCC Part 15 in the US prohibits the explicit control of specific channels for communication. Thus, packet collisions can only be avoided if readers within close proximity operate at different times. Some RFID reader anti-collision protocols have been proposed in the literature (e.g., scheduling-based [47], coverage-based [48]). However, many of these protocols require centralized computation and do not allow distributed computations, thus limiting the scalability of these proposed approaches.

7 Conclusion

The skyrocketing cost of healthcare in practically every country of the world are pushing governments and healthcare providers to seek and deploy innovative approaches that can reduce costs and simultaneously improve healthcare services to patients. These are challenging goals for all parties involved in healthcare delivery. In this work, we investigate and propose a scalable RFID-based architecture that can be deployed cost-effectively and at the same time supports the delivery of accurate and timely healthcare to all patients. The various components of our proposed architecture are presented and their potential benefits have also been identified. We also present future challenges that RFID-based architectures are likely to face when deployed in the healthcare environments. Some solutions to address those challenges are also briefly discussed.

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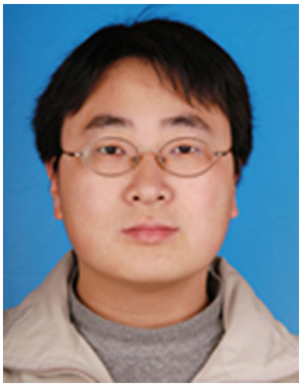

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