

Real-time location and inpatient care systems based on passive RFID

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Abstract— RFID technology meets identification and tracking requirements in healthcare environments with potential to speed up and increase reliability of involved processes. Due to this, high expectations for this integration have emerged, but hospital and medical centers interested in adoption of RFID technology require prior knowledge on how to squeeze RFID capabilities, real expectations and current challenges. In this paper, we show our lab tested solutions in two specific healthcare scenarios. On the one hand, we analyze the case of a medical equipment tracking system for healthcare facilities enabling both real-time location and theft prevention. Worth-noting aspects such as possible EMI interferences, technology selection and management of RFID data from hospital information system are analyzed. Lab testing of system reliability based on passive UHF RFID is provided for this case. On the other hand, we analyze and provide a solution for care and control of patients in a hospital based on passive HF RFID with the result of a fully functional demonstrator. Our prototype squeezes RFID features in order to provide a backup data source from patient's wristband. It also provides an offline working mode aiming to increase application reliability under network fail down and therefore, improving patient's safety. Considerations regarding lessons learned and challenges faced are exposed.

Index Terms— *Real-time location system, medical asset management, EPC Gen1&2 performance, inpatient management, hospital information system*

I. INTRODUCTION

Radio frequency identification (RFID) technology enables a seamless link between any physical tagged entity and the business information infrastructure providing lightweight computational and communication capabilities. Due to this, RFID is receiving considerable attention and is considered to be the quintessential pervasive computing technology [Rieback 2006] and the next wave of the IT revolution [Tzeng 2008]. As a consequence of the identification, tracking and tracing nature of RFID, organizations can acquire detailed data on property and location information that increases their ability to monitor the history, location and changing states of mobile wirelessly scanned entities. The adoption of RFID

technology is being embraced in a wide range of applications; including retail industry, supply chain management, anti-counterfeiting, security and transit systems.

In recent years, high expectations for the integration of RFID in healthcare scenarios have emerged. By exploiting RFID characteristics and possibilities, this technology is considered to have the potential to enable better service to patients and end customers while underutilization of equipment and mistakes in patients' treatment can be minimized. A proper management of RFID technology may improve the quality of medical processes making patient care more reliable and consistent, lowering costs and providing the tools to properly manage and trace material and information flows [Kumar 2009]. In spite of recent research interest in the healthcare environment, RFID adoption is still in its infancy and a larger number of experiences need to be collected and studied [Tzeng 2008] in order to better understand how to exploit RFID capabilities.

A highly concerning healthcare application is real-time tracking and location of medical assets. Medical centres have to face continuous losses of high-value assets each year [Bacheldor 2006]. Furthermore, equipment whereabouts are frequently unknown. Medical staff needs to sacrifice patient-care to find assets locations. Moreover, unneeded equipment is acquired or rented while the existing one remains underutilized. In this paper, our first case study focuses on this particular scenario. Our solution for real-time tracking of medical devices in a healthcare center is presented which consider anti-theft capabilities and partial automatic inventory. Beyond the presentation of our approach, several worth-noting and commonly overlooked aspects in the development of the solution are discussed such as electromagnetic interferences of RFID in medical equipment, RFID branch technology selection and management of the data generated by the RFID infrastructure from the healthcare information system. The real-time tracking solution is based on passive UHF RFID technology, a field where few previous results are available in literature. We measured the performance and reliability of the system in a laboratory experimental environment and the conclusions of our tests are provided.

In a different perspective, inpatient care and safety can be greatly enhanced by means of RFID technology. Every step in the patient care process can be seamlessly integrated in the information system preventing manual input mistakes, assisting caregivers in patient treatment and enabling in-depth analysis of medical staff workload to increase efficiency of

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personnel allocation. But current inpatient care pilots do not make the most out of RFID capabilities. In the common approach, RFID unique identification codes are used as license plates to query and update the backend information system. However, the limited storage resources in staff and patient RFID tags can be exploited as a complementary data source to enhance patient safety and overall system reliability in determined circumstances. In our second case study, the latter approach is adopted where a prototype of a passive HF RFID patient care solution has been implemented. Further than introducing our solution, selected lessons learned and challenges found during the prototype development are discussed.

The remaining of this paper is organized as follows. In Section 2 we present an overview of current applications of RFID in the healthcare environment and existing experiences and pilots gathering their first results and situation compared to our case studies. In Section 3, our first case study is focused on real-time tracking of medical assets. Discussion on relevant development aspects and results of our passive UHF RFID lab experiments are provided. In Section 4, our second case study related to a patient care and control solution for medical facilities is presented. Our approach of exploiting RFID tags as a secondary data source for critical data, as well as lessons learned and discovered challenges are discussed. Section 5 concludes the paper.

II. RFID IN UBIQUITOUS HEALTHCARE ENVIRONMENTS

In these scenarios, every single process is critical and must be addressed with the highest level of precaution and inspection to minimize risks and improve patients' safety. In order to achieve this reliability level, implementation of RFID technology may be crucial to accomplish tasks as: ensuring right identification of each patient and his corresponding medical data anywhere in the hospital, guarantying appropriate actions are granted to the right persons (drugs administration, surgical procedures, ...) regardless the time and place, identifying lab samples (blood, urine, exudations, biopsies, etc), verifying authenticity and origin of drugs and checking their status and expiry dates while they are moved among different departments and sections, etc. Additionally, inventory control of medical equipment or theft prevention of devices and medical utensils is also susceptible to be accomplished ubiquitously by means of RFID technology. In order to control location of medical devices, tracking equipment in real-time by means of RFID technology would allow finding and accessing required material anytime (but in a shorter time period) and anywhere.

Nowadays, there are initiatives and pilot projects that cover these needs in the healthcare environment:

Identification of blood containers: Productivity and safety of the blood product supply chain can be greatly enhanced by means of RFID. In [4], authors assessed tag readability and performance in this environment, as well as tested temperature and biological effects of RF energy on blood products. They

concluded that HF RFID performs adequately and safely for blood products, RFID has an impact in productivity and quality gains due to less process errors, better inventory management and avoidance of product discards. Moreover, regarding return on investment, authors calculated a pay-back period of 4 years for a mid-size blood centre collecting 225.000 units/year.

Further practical implementation in the area includes a pilot in four Italian hospitals [3] where EPC Gen 2 RFID technology has been implemented to track all steps of the transfusion process from taking blood samples to the final blood transfusion. As an output of this practical implementation, human mistakes which could turn into lethal results were dramatically reduced in the processes of drawing donated blood, transporting it and administering it to a patient, reporting an error reduction by 100 percent, as well as work-reduction times.

Identification of drugs: The U.S. Food and Drug Administration published a report [10] recommending the use of RFID technology to fight the chronic and expensive problems of drugs counterfeiting. Companies such as Exagera Technologies with his eShepert system that combines RFID and WiFi technology are supporting this goal. Sun Microsystems presented his own solution on this topic called "RFID Industry Solution for Drug Authentication" [Sun 2009] which provides lightweight EPC-based pharmaceutical authentication comparing EPC data on the RFID tags with available data in a central repository, as well as a supply chain-wide pedigree authentication. RFID has also been applied to anticancer drug management system [11] demonstrating its clinical usability. From a different perspective, from 380,000 to 450,000 preventable adverse drug events occur each year in the United States. Due to this, RFID has been integrated in the inpatient medication administration system [5] reengineering the inpatient medication processes in order to decrease the risk of these adverse events.

Tracking and control of medical equipment: several pilots based on active RFID technology have taken place with the purpose of tracking medical equipment inside a healthcare facility. In particular, a pilot in San Diego Medical Center [Sullivan, 2009] tracking a wide range of assets (e.g. IV pumps, SCDs, crash carts, gurneys, ...) have demonstrated return of investment: infusion pump rental fees were reduced from 8000 USD month rental prior to the pilot to a stabilized 2,300 USD/month during the pilot. Considering the complete range of tracked assets saving were estimated to approximately 450,000\$ for 2008. Regarding the use of passive RFID technology for tracking medical equipment, very few test results have been published. To the best of our knowledge, the most similar approach to our first study case was the passive UHF RFID trial which took place in the Wright Patterson Medical Center. The results of that trial [Alien 2007] showed a 85% accuracy rate in location of medical equipment. However, the report was published by a

division of a known RFID vendor and their accuracy tests did not specify adverse conditions as the ones exposed in our prototype.

Tracking of medical staff and patients: As a consequence of Severe Acute Respiratory Syndrome (SARS) where thirty-seven patients died and part of the medical personnel was also infected the Ministry of Economic Affairs in Taiwan granted research funds to support the implementation of RFID in healthcare. The experience of five early adopter hospitals has been presented [Tzeng 2008]. Authors conclude that future empirical research will be helpful in validating their propositions requiring a bigger number of experiences collected and studied. However they consider RFID useful in enhancing patient care and analyzing workload of medical staff.

A patient- and employee- tracking system [Swedberg 2009c] based on active 433 MHz RFID technology is currently being tested at Massachusetts General Hospital. The pilot gathers information regarding patient flow and bottlenecks with the expected outcome of gaining a better understanding of how the clinical system behaves. It will potentially reveal aspects such as how long a patient sat alone in an examining room or whether the medical personnel spent the proper time with the patient. An experience of tracking elderly patients suffering from dementia was also tested in the Albert Schweitzer II Hospital with the purpose of providing real-time location and an alert system if a patient goes beyond his expected location [Holzinger 2008]. Medical personnel provided positive feedback, but patients themselves reacted negatively to the idea of surveillance.

Patients' identification and care: a wide range of RFID-based solutions are emerging where this technology seamlessly identifies the patient in the information system and helps to improve patient care. A few Italian pharmacies [Swedberg 2009] are piloting a RFID system where customers are provided passive 13.56 MHz RFID cards which allow to track prescription purchases as well as create a health diary storing the results of screenings (e.g. glucose or blood pressure levels). Treatment documentation in large scale emergencies can also be automated by means of RFID technology as has been validated in [Hassinen 2008] where RFID bracelets and wireless sensors are used to automate documentation processes. This approach reduces manual paperwork in emergency situations enabling medical personnel to focus on patient care. In a similar perspective to our second case study, an RFID-based patient management system is discussed in [Chowdhury 2007] where patients are assigned a RFID wristband for identification purposes, but their approach does not take advantage of storage capabilities of RFID devices. The unique identification code provided by the wristband is only used as a "license plate" and all related data is stored and recovered in a backend server as in traditional non-RFID patient management systems.

Examples described here show an increasing interest by hospitals and health centers in integrating RFID technology in their processes. Recent initiatives have started to show that

radiofrequency identification systems, in addition to improve patient's security and reliability of processes, are able to produce a return of investment as has been previously exposed. Based on these results, a larger number of healthcare applications will consider applying this technology.

However, as these first pilots recognize, RFID adoption in healthcare environments is still in its infancy and a larger number of experiences need to be collected and studied [Tzeng 2008]. Many aspects of RFID adoption are yet to be discussed in literature such as safety of RFID electromagnetic fields in medical facilities, suitability of each technology branch for specific healthcare case scenarios and how to further squeeze RFID capabilities to enhance medical processes.

Regarding existing pilots on tracking and control of medical equipment, most of them have focused on active RFID technology. A very reduced number of experiences based on passive UHF RFID technology have taken place. The most similar one available in literature has reported a highly reliable and accurate real-time locating system, but it has been supported by an RFID vendor and the system did not specify reading tests in adverse conditions. In the context of our second study case, existing inpatient care and management pilots do not make the most out of RFID possibilities. As we show, it is possible to take advantage of on-patient storage capability provided by RFID devices combining this data source with traditional backend servers to track the most critical and relevant data in patient treatment which will be available even in case of network connectivity issues.

Further than exposing our approaches and prototypes solutions which could be of interest to future healthcare pilots in this area, we highlight several overlooked aspects in concurrent prototypes regarding RFID technology suitability for the proposed study cases, advantages of implementing RFID in these scenarios and current limitations and deficiencies (e.g. the necessity of a standard for globally adopted codes, data format and encoding in the storage of healthcare information in RFID devices).

III. CASE STUDY 1: TRACKING OF MEDICAL DEVICES IN A HEALTHCARE CENTRE.

One of the main issues which medical centres have to confront is the management of the medical devices, equipment and supplies. Equipment usage patterns are largely unknown. As a consequence, high-value assets remain inadvertently underutilized while unneeded equipment is acquired or rented. Moreover, medical staff can not readily find available equipment. As a result, personnel need to sacrifice patient-care or lose productive hours searching for the required equipment. Furthermore, hospitals experience alarming losses of assets each year [Tzeng 2008], approximately 10 percent of the assets are stolen or their whereabouts are unknown [Bacheldor 2006]. By the introduction of real-time location systems (RTLs) hospitals can enhance these processes. Some hospitals have already reported a remarkable cost reduction in rental fees [Sullivan 2009] and adoption of RTL systems have

been reported to produce return of investment in less than a year.

In a first approach, our application based on RFID has focused on providing smart identification capabilities to medical devices, equipment and utensils in a way that they are seamlessly integrated in a deployed ubiquitous infrastructure. Thank to this approach, tracking abilities of each identified element are provided in a manner that its path and real time location can be known as they move through the hospital. Any tagged tool can be found reducing exploration times. By using control rules, anomalous situations in which objects are moved out of their working area or extracted from the hospital without previous authorization are detected. As a last remarkable feature, the system allows to make a partial automatic inventory.

Architecture of the infrastructure requires arcs placed on the separation points between rooms or zones to distinguish (see figure 1). Arcs detect any appearance of an object under control that has been equipped with an RFID tag, generating a crossing event. By means of wireless access points, the different elements of the information system are connected to the network without requiring any installation of UTP wiring. Surveillance IP cameras allow to take images if alarm is raised under any circumstance.

A. Health issues, distortion of lab samples and EMI incidents

According to HID Corp. [21], electromagnetic radiations produced by HF RFID are not harmful due to power levels are under the limits of the standard IEEE C.95-1-1991 [31] that refers to the electromagnetic fields exposition levels that are considered safe for human beings. Also, interferences with pacemakers and ICDs (Implantable Cardioverter Defibrillators) are not feasible according to the emission power used. This includes pacemakers compliant to standard CENELEC EN 45502-2-1 [32]. Anyway, the World Health Organization [20] points that further research on this topic is required. [Van der Togt, 2008] assessed electromagnetic interference from active 125 kHz and passive 868 Mhz RFID inducing incidents in critical care medical equipment. In 123 EMI tests, RFID induced 34 EMI incidents (22 hazardous incidents, 2 significant incidents and 10 classified as light). These results indicate that implementation of RFID in the critical care environment require on-site EMI tests. Further research is necessary about electromagnetic interferences on medical equipment and devices, as well as the effects of RF energy on the human body. Depending on the specific healthcare application where RFID is implemented, additional research may be required. As an example, RFID tags could be attached to blood products for tracking purposes. However, RF energy could potentially alter blood samples provoking a distortion in test results. In this regard, [Davis 2009] have investigate the temperature and in vitro effects of 13,56 Mhz radiation on WBDP and RBC products under FDA-approved

protocol. Authors concluded that no significant rise in temperature or increase in cellular/protein degradation was caused.

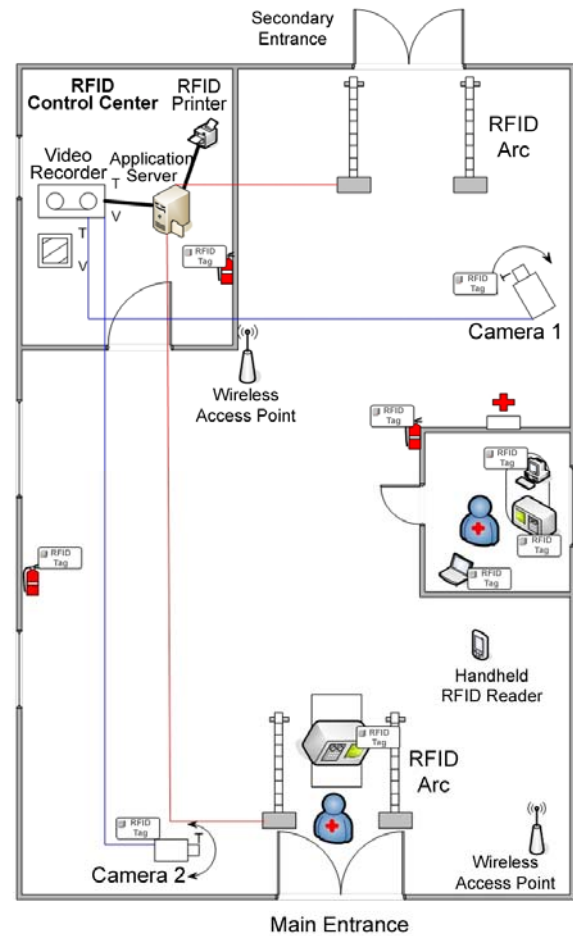


Fig. 1. Diagram of medical devices control based on RFID

B. RFID technology evaluation and selection

RFID technology based on HF has achieved a high degree of maturity and adoption of its standards. Available solutions are divided between those based on ISO 14443 [1] (as well as on proprietary implementations from different manufacturers as the well-known MIFARE [26] from Philips, now NXP Semiconductors) and those based on ISO 15693 [2] (including derived solutions as Tag-it [28] from Texas Instruments, I-Code [27] from Philips or My-D [29] from Infineon). First type of tags are oriented towards security applications, like access control or electronic payment, while the second type is used in a wider range of solutions of different nature, including the monitoring and control patient solution presented in this paper.

At a first sight, RFID based on HF might be a proper technology to develop the proposed solution for this ubiquitous healthcare scenario. There are commercial solutions of arcs designed to control crossing events in a corridor that include EAS (Electronic Article Surveillance) capabilities to protect against thefts. Additionally, it has a high level of resistance against metals and liquids presence. But it

presents a reduced reading range with a maximum distance between arcs of 1,5m which is not enough for the width of corridors of a hospital.

On the other hand, passive UHF RFID presents multiple characteristics that turn it adequate for the proposed application: a reading range of 4-10 meters. It is oriented to infrastructures with a high number of readers with a centralized processing of events, offering advanced features for filtering and different network interfaces to integrate readers in the system. There are middleware layers that provide a unique interface to access all data generated, with a higher level of abstraction and in a manufacturer independent format.

UHF readers are more complex and provide more advanced features than HF readers. They are ruled by sophisticated firmware or operating systems that allow integrating the filtering and processing of RFID events at the reader itself, so network is not overloaded with raw events. Features integrated in readers include Ethernet or WiFi connection and the possibility of remote control and maintenance. However, existing readers are oriented to be used in supply chain environments, their main application nowadays, so they are rough solutions designed for the hardness that this context requires. Regulations, dedicated bandwidth and transmission power allowed is not homogeneous all around the world [Ecosensa 2009] which affect the range of products available in each region. An evolution from EPC Gen 1 [3] to EPC Gen 2 [4] has taken during the lifetime of our project, unifying EPCGlobal and ISO 18000-6c standards and favouring interoperability.

Regarding active RFID technology, it offers a comparable reading range to passive UHF technology (i.e. 4-10m, although some solutions reach up to 2km), superior onboard memory and computation capabilities and tolerance to water and metal materials. Due to this, it has already been piloted in healthcare prototypes [Swedberg 2009c], [Sullivan, 2009]. However, several disadvantages turn this technology branch less appealing. Cost per tag (20\$ and up [Roberti 2009]) and volumen are high. The smallest active RFID tag from one of the leading suppliers [Savi 2009] has a size of 6.2 cm. x 1.7 cm x 1.2 cm. These characteristics turn them inappropriate for tagging utensils and small sized devices as desirable in our solution. Tags present a reduced time life due to the use of battery as power source requiring periodic maintenance. Furthermore, active RFID technology is not as mature as passive technology alternatives. Most solutions are based on proprietary protocols with non interoperable products. The recent ISO 18000-7 standard for 433 Mhz active RFID technology has emerged as consequence of the strong investment of U.S. Department of Defense in active technology and heavily relies on intellectual property owned and developed by Savi, the main DoD active technology hardware vendor [RFIDUpdate 2006]. DASH7 Alliance [DASH7] has been formed, but the standard does not equate to interoperability yet, as products from different vendors

which comply with the standard do not talk each other [Burnell 2009]. The RFID Center of Excellence at the University of Pittsburgh currently certifies conformance to ISO 18000-7 standard, but an interoperability certification program has not yet been developed.

Due to these handicaps in active RFID technology and the potential benefits of passive UHF RFID technology for this asset tracking scenario, the latter technology was selected for our case study.

C. Management of RFID infrastructure from the medical information system

An RFID infrastructure deployed in a medical centre can generate a huge amount of information about medical processes. Once the semantics of this data has been properly interpreted, it can not only inform about the current location of a medical device, but throw light on how the available resources are managed, how to increase equipment availability or which rented equipment would not be necessary to name a few.

However, real data produced by the RFID infrastructure consists of an overwhelming amount of raw RFID detection, gate crossing and management events. Each RFID event will update the system status, but the healthcare information system should not handle all these low level information directly. Instead of taking care of all these aspects in the final application, the use of a middleware is recommended which can handle the high volume of RFID events and provide a unified interface and semantics to access a wide range of RFID readers.

At the lowest level, this intermediate software layer should provide drivers or adapters able to connect RFID devices from different vendors and standardized protocols to the information system. Once devices are logically plugged into the system, the middleware must provide event managing services including capture, filter and storage of RFID events. Filtering should be performed in such a way that only relevant data reaches the network and, finally the healthcare application. Medical processes logic could be modelled in the middleware in such a way that filtered and aggregated data events can be semantically processed and dispatched to the adequate entities. A query layer could be included in order to request current or historic data for tracking and monitoring purposes. Finally, the middleware should provide an application integration interface in order to integrate this middleware into the healthcare equipment management system.

A middleware layer can also act as a firewall between the physical RFID tags attached to medical equipment and the healthcare information system. As demonstrated in [Rieback 2006], even if passive RFID tags have basic computation capabilities and act as highly constrained storage devices, they can be used to execute several attacks on the backend system such as buffer overflow, code insertion and SQL injection attacks. As a result, the intermediate software layer should

carefully validate any input information from the RFID devices, as well as provide access control and authentication of participating entities, data integrity and confidentiality.

Although security aspects are not clearly exposed in current middleware solutions, several alternatives have emerged during the last years which cover most of the basics points discussed such as Sun Java System RFID Software, Oracle Sensor Edge Server [Oracle], Sybase RFID Anywhere [Sybase] and Microsoft Biztalk RFID [Biztalk]. These solutions were originally designed for item tracking in the supply chain which remain reflected in part of the terminology and functions (e.g. Pallet Shelf Filter, Pallet Pass Filter), however their comprehensive functionality can be straightaway adopted in healthcare environments.

For the construction of our prototype, we used Oracle Sensor Edge Server which provided extensible dispatcher, filter and drivers frameworks. A virtual RFID event dispatcher allowed us to validate our software prototype before integrating real RFID UHF readers. In the last phase we tested the reliability and accuracy of EPC UHF RFID technology for our proposed real-time location and alarm system which provided disappointing results for its adoption in our healthcare scenario.

D. Performance of passive RFID UHF technology

The testing environment set up has been formed by a corridor made of a metallic mesh. Attached to the mesh there were six different models of antennas, including linear (vertical and horizontal) polarizations as well as circular polarization antennas in order to test diverse combinations. UHF RFID readers tested were Intermec IF4 and IF5 [22], compliant with specification EPC Gen1 [3] and working under the limitations of standard ETSI 300-220 [6]. Tags used during tests were designed for cardboard and paper surfaces, caused by a wider selection of models still needed to be commercialized.

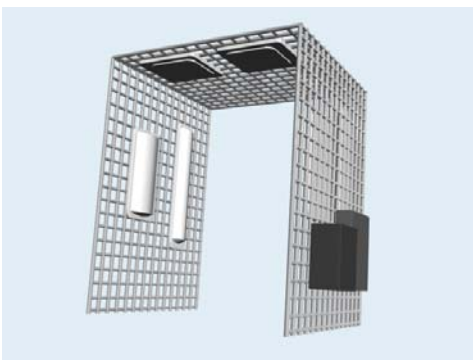


Fig. 2. Diagram of the testing environment

After several tests simulating possible reading scenarios that can surge in the context of the proposed application using different configurations of readers and antennas, the following conclusions were achieved:

- Two tags that are in physical contact with each other or face to face in a distance of a few centimetres can not be read.
- As expected, a tag outside the specific reading zone of the

antenna is not read. Non-expected restrictions come from the fact that size and shape of vision area is really limited and depends on the size of the antenna (20 – 50 cm) and the opening angle of its field (20 – 60°).

- Orientation of the tag has an important impact on its reading ability. In order to be read, it is almost necessary that the tag is in a parallel plane to that of the antenna (in case of a circular polarization antenna) and with the same orientation in the case of linear polarization antennas.
- A tag in physical contact with a hand or a human being in the middle of the direct line of sight between the tag and the antenna, due to the high proportion of water in the body, completely blocks the reading process.
- A tag in physical contact with a metallic object could not be read in any of the tests. Metals reflect electromagnetic waves, so in theory, depending on the particular situation, they can improve or interfere in the reading process. In an arbitrary scenario its behaviour is not predictable and none of our tests simulating crossing events conducted to a successful reading.
- If none of the previous issues is replicated, reading distance was not a limiting factor in our scenario. Using linear polarization antennas with the lowest gain placed in the ceiling were able to read the most remote tags leaning on the floor.

Consequently, identification of tagged elements by means of passive UHF RFID technology, even if it is functional, requires highly specific conditions. The reading process needs to be done in a controlled environment where aspects like position and orientation of the tag, relative location to other tags and surrounding materials are known and controlled.

In particular, integration of medical devices in the proposed ubiquitous environment requires tagging of equipment with metallic cases. Crossing events of tagged elements under the reading arcs will involve medical staff in the proximities. Therefore, a high risk of interferences during reading operations due to human beings is feasible. At the same time, orientation of tags is variable as not every tagged element can be expected to cross in the same physical orientation.

Even though our tests were performed with EPC Gen1 readers and tags, reflection and attenuation issues of UHF electromagnetic waves regarding metals and liquids are intrinsic to this frequency range and accentuated by the weak back-scattered signals produced by passive RFID tags.

As a result, new revisions of this RFID technology branch are condemned to share these handicaps. Several manufacturers (including Checkpoint, Sirit Inc. and CAEN RFID) have confirmed that “our results are consistent with EPC Gen2 expectations”. In spite of new generation improvements, a state of the art EPC Gen2 tag enclosed in a metal box can not be read at any distance. Regarding water attenuation, a tag accidentally covered by a nurse’s hand, even with a high performance tag (such as the Alien ALN-9554 M) and reader, would reduce reading distance from 5-8m to less than 1m with unreliable reading accuracy.

As a result of this analysis, reliability of RFID UHF passive technology in the proposed application can not be guaranteed and the explored anti-theft features can not be fulfilled by passive UHF RFID technology.

IV. CASE STUDY II: PATIENTS' CARE AND MONITORING

Adoption of RFID technology in hospital information systems has the potential to greatly enhance the patient care process. Patient data can be seamlessly linked to HIS system providing instant access to relevant information and tracking patient's treatment. Thanks to this integration of medical processes, incorrect data input can be prevented and errors in patient treatment or missed drug administrations can be detected in real-time, reducing potential for incorrect or delayed diagnosis. Each event in the inpatient care process can be introduced in the information system recording doctor and patient interactions. In this way, the analysis of medical staff workload is facilitated providing the tools to increase staff efficiency and optimize manpower allocation.

In this section, we present a system to monitoring and care improving of patients admitted in a medical centre facility. In order to achieve these results, the application assists medical staff in the identification and medical data retrieval of patients, as well as offering a higher level of patient's security in the process of monitoring his treatment thanks to the support of RFID technology. The described application has been implemented obtaining a fully functional demonstrator of a patients' control system based on passive HF RFID technology.

In this application, radiofrequency identification technology provides advantages in two different ways:

Identification needs: technology facilitates medical staff and patients' identification tasks, so providing an easy way to access their medical data and treatment regardless patient's location or consciousness state.

Information source: in the situation of a failure of a central server or hospital's network, onboard memory on RFID tags has been used as a backup information source for critical medical data, so patient's care is not interrupted.

In our application, each member of the medical staff accesses the system from a PC or a mobile device (PDA) that integrates an RFID reader (figure 3) from any location covered by deployed wireless network. Once he has been authenticated in the application (by means of his RFID card and personal identification code), he is able to perform a patient's identification through the adequate RFID wristband. From this point on, medical staff can access personal medical information regarding the patient that is available in the central server, check scheduled actions, perform them or order new tasks. Thanks to the centralized data handling, actions performed and their results are immediately available in the system to the rest of the medical staff involved.

Intelligent and automated tracking at server level for every

single action carried out on the patient provides an improved knowledge of patient's state, as well as facilitating manual supervision of pending and finished tasks. An alert control system manages status progress of pending tasks for all the patients. In case of a delay on the specified schedule for the action, a warning message to relevant devices (i.e. nurses assigned to patient's area or entrusted doctors) is sent, so foreseeing oversight in patient's care.

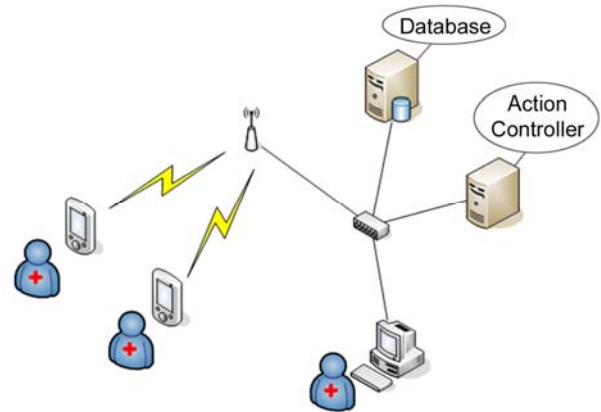


Fig. 3. Example of application scenario

In a schematic way, the main key features of our patient monitoring system are the following ones:

Medical staff authentication: it is performed by way of their RFID card and personal identification code. Authentication is necessary to access application.

- *Patient's identification:* if patient is not present, it can be done manually, however it is usually facilitated by reading patient's RFID wristband.

- *General medical information retrieval:* available from the central server once a patient has been identified.

- *Critical medical data retrieval:* available from central server, but also from patient's RFID wristband. In case of a server or network failure, main data and last performed actions can be read from the wristband regardless network status.

- *Handling of required tasks on patient:* Query of foreseen and already done actions, as well as order new ones or perform pending tasks (e.g. drug's administration, take patient's temperature or blood pressure, change bag of serum, etc.)

- *Event's data recording:* who order it, who performed it, how long they delay was, task's results, working mode of each step, etc.

- *Local working mode:* In case of network failure, device changes its working operation to local mode where it is able to continue working thanks to the data available from RFID tags. Any new data generated is stored on the device itself temporarily for subsequent synchronization with central server.

- *Alert control system:* a monitoring server checks that every planned action is done on schedule, otherwise a periodical warning message to pertinent medical staff (e.g. devices where they are logged in) are sent.

- *Data synchronization*: Once network is available again, every local action is synchronized with the central server, detecting and solving data redundancy and conflicts.

- *Automatic working mode change*: if network's connection problems are detected, online working mode is changed to local working mode automatically. Network availability is supervised to restore online working mode as soon as possible. Although medical staff is warned about connection issues, application interface is transparent to working mode and interactions are completed in the same way.

Medical staff RFID card: it contains indispensable information to identify the individual, authenticate and authorize access to the system. It is essential in local working mode.

Patient's RFID wristband: it contains basic identification data, critical medical information (e.g. blood group, allergies...) and last performed actions, to be attended in case of an emergency (local working mode).

Data privacy: information stored on RFID cards is encrypted so it is unavailable to third parties.

Regarding RFID technology, we have used passive RFID based on HF compliant with standard ISO 15693 [2] for vicinity cards. Features of this technology have been already explained. Commercial products available make it the ideal choice for the proposed application.

RFID reader: we have chosen the RF PC Handheld Reader from ACG [24]. It integrates a compact flash interface. Therefore, it can be used in handheld devices used by doctors and nurses during their examination rounds and laptops (via a PCMCIA adaptor).

RFID tags: patient's wristbands were provided by PDCorp Precision Dynamics Corporation [25] that offers a family of RFID bracelets designed for healthcare. Our model has a capacity of 256 bytes (64 memory pages with 4 bytes/page).

The software application follows a *model-view-controller* (MVC) architectural pattern. This approach allows using the same control logic and data model in personal computer and handheld device versions, only varying the user interface.

Data flow from application to RFID reader is shown in Figure 4. At application layer, information is managed in a high abstraction level (e.g. in terms of blood type, patient's name or PIN code hash). In the data mapping layer, this information is translated in the data structure defined for optimizing tag's memory where each data element is transform into a sequence of bits that minimizes storage requirements (e.g. name of allergies are looked up in a table and translated into a bit code). The cryptography layer provides seamless encryption and decryption of data between data mapping and in/out layers. AES block ciphering and RC4 stream ciphers were tested. While the first option provides stronger security, it requires reading and writing a higher number of bytes which are slow operations in RFID tags. In/out layer sends specific RFID reader commands to the

wrapper that communicates with the interface of native RFID reader API. Reader interfaces of passive HF RFID readers are not unified, but vendor specific. Thanks to this modular design different reader models or cryptographic algorithms could be integrated in the application without drastic changes.

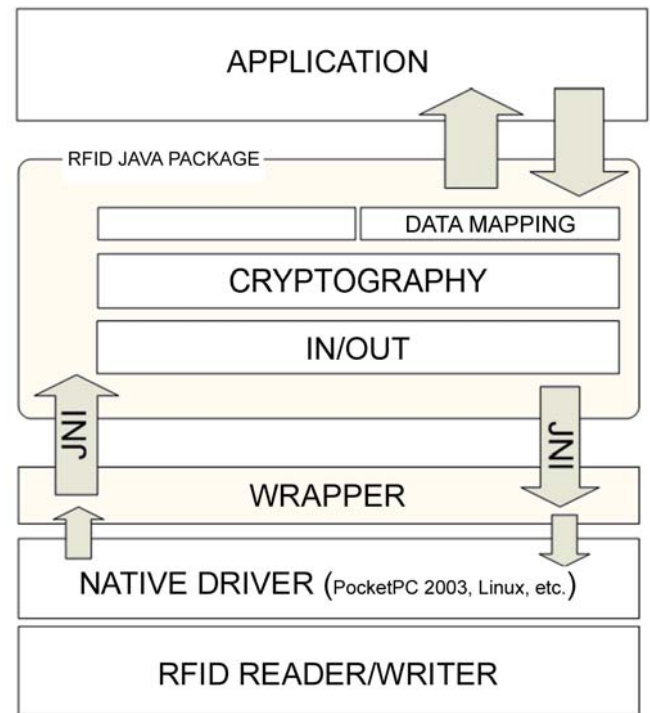


Fig. 4. Layer model of communication between application and RFID reader

Due to wireless nature of proposed network, risk of failure in connection availability to central server is not negligible. For this matter, a local working mode has been implemented where every crucial data necessary to continue with application normal operation is obtained from handheld device itself or RFID tags from personnel or patients involved in the operation. These devices work as a backup information source in this situation. Any data generated at local working mode is stored on the PDA waiting for synchronization with central server. Critical information is also stored on patient's wristband so it will be available, even if patient is moved to a different area and network inconveniences continue as relevant data is seamlessly carried by the patient itself. This way, any doctor that identifies the patient will have access to this data regardless of the device used or working mode. Transition to online mode is transparent to the user and, at the moment of recovering network access, central server information is updated.

Selected data stored in RFID tags

Due to the limited onboard memory of RFID tags, as well as reduced read and write speeds, only a minimum data has been selected to be stored in tags. This restricted dataset enables almost complete access to the application in local mode.

In order to authenticate a member of the medical personnel, grant right permissions and log activities in local mode, the following data is stored in the card: user identification code, name and surname (for visual verification of identity recognition), hash of PIN code and user role.

In case of the patient, center of the system, memory requirements include a larger basic dataset, including identification data (person unique ID, name and surname), critical, but static medical data (blood group and known allergies), as long as dynamic data about current treatment state (record of the last actions performed, including action type, a timestamp and action specific properties as dose for drug administration).

With the purpose of optimizing memory, each data element was defined and coded at bit level, resorting to allergies coded by a table of most typical allergies and limiting timestamps precision level.

A. Conclusions and challenges regarding the solution

Among its features, our lab patient's care solution provides seamless patient's recognition and medical data retrieval. As an important source of medical errors are related to human mistakes in patient's data entry, recognition and assignment of right medicament (in fact, patient identity errors can account for as many as 35% of all medical errors [33]), patients' safety would be substantially improved by means of RFID based procedures. In the proposed scenario, where RFID capabilities are not challenged (i.e. only one tag in reading field exposed at least during tenths of a second), reading reliability is virtually 100 percent accurate [35]. A reading mistake with a near patient's wristband is not a realistic risk as reading range in our tests was up to 45 mm.

Available RFID wristbands were based on ISO 15693 which does not provide any security mechanism in order to ensure data confidentiality and integrity. In fact, ISO 15693 does not provide protection on the read command, no onboard encryption or authentication and only optional password protection on the lock and write commands [34]. As a result, security has to be implemented in the application itself, being limited to encrypt and/or sign stored data (signing would further restrict tag's midget memory). This approach does not prevent third parties to be able to read and, therefore, later offline attacks could occur. Also, it increases reading/writing time.

In our tests, stream ciphers such RC4 do not affect reading time due to only necessary bits being transferred. However, a static encryption key is required to guarantee accessibility to offline devices decreasing security and enabling plaintext attacks. As a consequence, a block ciphering scheme based on AES was used adding a random bit sequence padding at the end of each block to prevent static ciphertexts. However, reading and writing times were raised to the order of seconds, thus affecting usability.

In our opinion, RFID wristbands should comply with a security concerned standard like ISO 14443 that was designed for applications such as access control, public transport and

digital documentation. ISO 14443 and derived tags (e.g. Mifare RFID tags) provide advanced security features including cryptographic challenge-response authentication, 128-bit AES, triple-DES and SHA-1 algorithms.

Our proposed offline working mode uses RFID tags' memory as a backup information source to ensure crucial data availability. However, in order to store last actions' data on patient's RFID wristband, medical personnel is required to bring RFID reader over twice: at the beginning for patient's identification and data retrieval, and at the end of patient's care to update contents. Even though in theory, devices could remain in offline mode as long as needed because data required for normal operation would be available, it is important to point out that decisions made by doctors without physical proximity to the patient would be based on data available online. As a result, devices should recover connectivity and perform the automatic synchronization process as soon as possible to minimize scrutiny based on outdated data.

As an additional consideration, small sized touch screens available in PDAs have turned out to be an inconvenient and arduous input data device. Handwriting recognition and onscreen virtual keyboards slowdown text input, even for expert users. Therefore, functionality of handheld devices should be reduced to tasks requiring minimal interactivity (i.e. confirmation of pending actions carried out or notification of vital signs' values).

In our prototype, the data selected to be included in the patient health summary stored in the RFID wristband (i.e. most relevant and timely core health information), as well as data representation and codification had to be defined as an ad-hoc solution. Available standards such as Continuity of Care Record (CCR) have been designed with standard computers on mind. Extremely resource-constrained devices such as RFID tags with onboard memory limited to 256 bytes can not handle CCR data: the high amount of sections (e.g. insurance information, patient demographics, medications, care plan, etc.) would not fit and XML textual data representation does not make the most out of tiny available memory. In order to facilitate interoperability of RFID-based healthcare systems, a standardized solution should be defined for highly constrained devices defining a core of critical patient's data and its representation at bit level.

This required standard should consider the definition of a lightweight electronic health record (EHR) adequate to be stored in extremely memory constrained devices (such as RFID tags). The format and representation of simple data types (e.g. time and date, dose amount) as well as more complex data elements which are common in EHR (e.g. medical history, allergies or billing information) should be defined with the purpose of providing an unambiguous encoding, structure and semantics of medical data stored in RFID tags while minimizing the number of bits required. Standardized minimum length identifiers and codes to refer to healthcare terminology covering a wide range of areas of clinical information, diseases and drugs would be required. In

order to avoid duplication of work, this medical terminology and codification system should be based and cross mapped to existing non-RFID oriented initiatives such as the Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT) promoted by the International Health Terminology Standards Development Organization (IHTSDO) or the International Classification of Diseases (ICD) published by the World Health Organization.

To the best of our knowledge, the most related standardization to our proposal is the recent ANSI/HIBC 3.0 2008 standard resulted from work carried out by Massachusetts General Hospital which defines the data formats for barcodes and RFID tags to positively identify objects in the processes of medication administration and management. This standard takes into consideration the limitations of RFID technology. However, it is limited to the specific necessities of medication delivery while other healthcare scenarios have not yet been addressed.

Finally, an adequate and unified interface between the hospital information system and the structured medical data stored in RFID tags should be designed taking into consideration the communication requirements of healthcare environments. As of 2009, each ISO 15693 / 14443 RFID hardware vendor provides their own application programming interface (API) to integrate RFID readers. Solutions range from proprietary APIs which are shared between all the readers manufactured by the same vendor (such as Gemtag's G2KCAPI [Gemini]), integrator devices which provide the required interface between multipurpose widespread middleware and RFID readers (e.g. Feig Device Provider for Microsoft Biztalk RFID [Feig]) and free RFID stack implementations (e.g. librfid [OpenMRTD] which unify the API between supported readers. A healthcare-oriented middleware should be provided in order to interface between standardized (e.g. HL7 compliant) messages transmitted inside the hospital information system and structured data stored in RFID tags.

V. CONCLUSIONS

In our first study case, we presented a tracking and control system for medical devices and equipment based on passive UHF RFID technology to facilitate real-time location and abnormal use detection. Although some reports on safety in RFID adoption in healthcare environments were found, evidences of electromagnetic interferences in medical equipment exist, thus further research in this topic is required. As discussed, healthcare information systems should not manage raw data offered by RFID infrastructure directly, instead the presented steps are recommended. Available middleware solutions, in spite of being designed with the supply chain management in mind, provide adequate core functionality. An analysis on the suitability of each RFID technology branch for the proposed scenario has been offered. A priori, passive UHF RFID technology presented worth-noting advantages over active RFID. As opposed to scarce

previous literature on the topic, our evaluation of technology performance in an experimental setup has exposed a low reading reliability of this RFID technology branch in the proposed environment. Due to this, we consider that passive UHF RFID adoption should be limited to scenarios (even healthcare scenarios) where restricting factors (e.g. tag physical position and orientation, as well as presence of metals, water or human beings) can be controlled or high reading accuracy is not required.

In our second study case, we have designed and implemented a lab tested solution for care and control of patients in a medical centre. RFID technology has been the basis to develop several features of the system that would improve multiple aspects of involved processes, providing seamless identification of medical personnel and patients, speeding up medical data access and treatment control. Exploiting possibilities offered by RFID tags onboard memory, we have obtained a backup information source for critical data that is available wherever medical personnel and patients move. In our prototype, this backup source has been essential for access control to the application, storing of most relevant patient's medical data and knowledge of the last actions carried out. Thanks to this in-situ information source, we have been able to develop an offline working mode to guarantee application operation and data availability in case of central server failure or loss of wireless network connection.

While RFID tags are commonly used as identity codes to lookup backend HIS servers, we believe solutions should further exploit the on-patient data source provided by RFID tags. The combination of both data sources has to be properly engineered to take advantage of this feature while guaranteeing data consistency. Encoding, format and semantics of medical data stored in RFID tags should be standardized. Additionally, middleware solutions to interface between high abstraction level concepts used in standardized HIS messages and proprietary application programming interfaces available in ISO 15693/14443 RFID readers are required. As enhancement in patient care processes as well as return of investment has been demonstrated in related literature, a bright future of RFID in healthcare can be foreseen as the detected shortcomings are mitigated and needed solutions and standardizations are developed.

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