On the Design, Installation and Evaluation of a Radio Frequency Identification System for Healthcare Applications

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Abstract—**In this paper, we present the design, implementation, and testing of a Radio Frequency Identification (RFID) system for healthcare applications. The constantly growing passive RFID technology at Ultra High Frequencies (UHF), in conjunction with current state-of-the-art Information & Communication Technologies (ICTs), was used for the system design. The end product was installed at an oncology hospital in Cyprus where it was thoroughly evaluated by medical staff and hospital administrators. This pilot project had three main objectives: a) automatic and error-free patient identification of in-hospital patients using RFID enabled cards or wristbands; b) Real Time Location Service (RTLS) for locating and tracking medical assets and high-value equipment in the hospital ward; c) quick and hassle-free drug inventory management through the use of inexpensive smart labels and cost effective stationary readers. Here, we present a detailed description of the three major sub-systems of the pilot project emphasizing the main features and capabilities of the system, important design and implementation issues, as well as system evaluation and testing. During the design stage of the project, special emphasis was placed on user friendliness, system capabilities, adequate coverage and tag readability, privacy and security of sensitive patient data, system reliability, and the daily practices of medical personnel and hospital administrators.**

Index Terms—**Radio Frequency Identification, Healthcare Information System, Real Time Location Service, Patient Identification, and Inventory Management.**

I. INTRODUCTION

IN recent years, the rapid advances in information technologies, electronic communications, wireless networks, computers, and semiconductor devices provided a conducive environment for the development and continuous growth of RFID technology in various sectors of the economy. More specifically, RFID systems found numerous applications in a wide range of fields, ranging from logistics, supply chains, vehicle tolling/identification, and retail business to industrial automation, internet payment systems, baggage tracking, and healthcare service [1].

An RFID system is made of an interrogator and the tags, which are classified as active, if supported by a battery, or passive, if not. In the case of a passive RFID system in the UHF band (US 902-928 MHz, EU 865-868 MHz), the interrogator launches a wave outwards which is backscattered by the tags. The energy captured by a specific tag antenna is rectified, and if the received power at the terminals of the attached chip is higher than the sensitivity threshold of the chip, the backscattered signal is modulated by allowing the chip to alternate between two distinct states having different values of input impedance. This pre-programmed switching between the two distinct states translates to a unique identification code of the tag (e.g., 96-bit EPC code).

Even though the potential benefits from adopting this emerging technology are significant, a large scale deployment of RFID systems is yet to come. Major obstacles to the widespread adoption of RFID technology include the cost of initial investment, the cost of tags, lack of successful business examples, need for adoption of new practices that process and analyze additional data, need for software customization dependent on the type of business, possible electromagnetic interference with other electronic equipment, proximity effects on system performance, etc. Many of these challenges, however, have been given considerable attention by the research community and, consequently, significant progress has already been achieved. For example, the adoption of RFID technology by the METRO Group, the third largest retailer in the world, attracted a lot of attention when they announced substantial labor reductions, time savings, efficient handling process, and elimination of out-of-stock situations [2]. Another successful story is that of Wal-Mart with a long-term experience on RFID technology in supply chains [3], [4]. The cost of passive RFID tags continuously drops, thus reducing initial investment and running cost, whereas the sensitivity of the tag's chip improves year after year allowing better coverage and enhanced readability.

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In this paper, we present our experiences in dealing with the design, installation, and evaluation of a pilot RFID system for a healthcare provider. The main objectives of the pilot system include: a) automatic and error-free patient identification; b) real-time location service for medical assets and high-value equipment within the premises of a hospital ward; c) drug inventory control and monitoring.

The proposed passive RFID system aims at improving traditional practices that take place on a daily basis in a hospital environment. For example, routine medical tasks such as drug prescription or drug administration are based on paper-bound processes that are prone to human errors due to possible misreading of the handwritten notes or, in the worst case, misidentification of the patient. The US Institute of Medicine estimates that more than 44,000 deaths occur every year in the United States alone due to in-hospital medication errors [5]. The number of people that die every year due to medical errors exceeds the number of deaths due to other causes such as breast cancer, traffic accidents, or AIDS [6]. Many of these errors could have been prevented by designing systems and/or processes of care to ensure that patients are protected from this type of accidents [5]. The US Food & Drug Administration (FDA) estimates that medical errors approach 40% in paper-based environments. History has shown that traditional paper-bound practices in hospitals may result in patient mix-up errors which often create serious health problems for the hospitalized people.

During the testing period of the RFID system installed at the Bank of Cyprus Oncology Center in Cyprus (BOCOC), in-hospital patients were given a unique identification code, in the form of an RFID enabled plastic card or wristband, which can be read from a close distance by a handheld UHF RFID reader attached to a light-weight medical tablet PC in the hands of a medical doctor or nurse. Once the patient is uniquely identified, the tablet is authorized to upload from the central database the patient's medical profile and other relevant information. This is the first major pillar of the project.

The second major pillar of the project is real-time monitoring of the drug inventory cabinet located in the hospital ward, near the nursing station. Drugs stored in the inventory cabinet are difficult to monitor on a daily basis. It is highly probable that drugs are removed from the cabinet without proper authorization. It is estimated that 10% of drugs in a typical hospital are lost every year due to possible thefts [7]. It is also possible that drugs expire without noticing or drugs run out of stock at critical times putting patients' lives into a real danger. Undesirable situations such as these can be effectively avoided if a monitoring system is in place inside the drug inventory cabinet. Such a system provides up-to-date and precise information on the quantity and type of drugs in the cabinet including drug name and brand, expiration date, manufacturer, and place of origin.

The third major pillar of the project is locating and tracking medical assets and high-value medical equipment in the premises of the hospital ward. It is often the case that medical equipment, wheelchairs, infusion pumps, or even patient files are forgotten in various rooms and, when needed, nursing/medical staff is searching for them all over the place wasting valuable amount of time. Almost one third of the employee's working time is wasted daily on searching for equipment and assets throughout the hospital [7]. This translates to lowering productivity and efficiency at workplace, which, of course, has financial implications on the running cost of the hospital. This problem can be alleviated by tagging equipment and patient files with passive RFID tags which can be effectively tracked throughout the hospital ward using a network of antennas and stationary RFID readers. This network of antennas covering a great portion of the hospital's ward must be carefully designed in order to provide adequate coverage and long-range readability [8]. Optimization of the precise position of the antennas within the hospital ward was achieved using effective ray-tracing models and measurements [9], [10]. Of course, there were many other issues involved in the design such as the physical size and type of the antennas used, electromagnetic interference with other medical electronic devices, the topology of the hospital ward, and recommendations and restrictions set by the medical personnel of the hospital. All these factors/issues had to be carefully considered by the research team during the design and implementation phase.

The hardware design of the pilot RFID system is provided in Section II. In Section III, the software design with emphasis on the implementation of the three main pillars of the application is presented. The evaluation of the system design is provided in Section IV. Finally, in Section V the paper conclusions are presented.

II. SYSTEM HARDWARE DESIGN

The heart of the system hardware is the server which hosts the database with all necessary information regarding patients' personal data and medical history, list of drugs with associated information such as type of drug and expiration date, list of equipment and medical assets to be tracked, administrator and medical personnel accounts, as well as information regarding daily practices and routine activities. Data on the server are backed up on a regular basis whereas sensitive patient information from the server can be retrieved only by authorized users with read privileges. Doctors have privileges to read and write patient information onto the server, whereas nursing staff have restricted privileges with limited access to medical information. The server is at all times connected to a Local Area Network (LAN) interfaced with a Wireless LAN (WLAN) network covering the area of the hospital ward where the pilot project was launched. Wireless Access Points (WAP) were installed at specific points within the ward in order to provide sufficient communication coverage everywhere. A tablet, like the ones shown in Fig. 1, in the hands of a doctor or nurse must be able to provide continuous and quick access to the WLAN at all times regardless of location. Exchange of sensitive information between the tablet and the server is done using a high level of encryption.

Fig. 1. Medical tablet PCs used in the implementation of the project.

The tablets employed in the project are equipped with a clip-on module that easily snaps onto the tablet and provides access to a USB and Ethernet port. A Class 1 Generation 2 (C1G2) USB stick-like UHF RFID reader/writer, shown in Fig. 2(a), was used for patient identification. Each patient is given a plastic ID card (badge), shown in Fig. 2(b), onto which an RFID label (inlay type) is attached. RFID wristbands, like the one shown in Fig. 2(c), can also be used; however, our experience with couple of brands had shown that readability could not be achieved at distances larger than a few centimeters. For this reason, we resorted to the use of inlay tags placed on the front or the back of a name badge. Using this type of inlay tag, in conjunction with the stick-like UHF reader, readability was recorded for a maximum distance of 80 cm. It was not desirable to achieve readability from larger distances in order to avoid identification of neighboring patients or other RFID-tagged objects. The only problem with the stick-like reader was the loose USB connection, which could affect readability, and the protrusion of the stick which was prone to damage or breaking.

For the purpose of RTLS, the pilot project had enough funding to cover a maximum of four patients' rooms, or three patients' rooms and a drug inventory cabinet. A C1G2 UHF reader/writer with four monostatic RF ports and Ethernet support was installed at a central point on the roof of the hospital ward. Two circularly polarized antennas were installed side-by-side in each of the rooms, approximately 2 m high from the floor. These two antennas were fed in phase through a 2-way, bidirectional power splitter/combiner having a low insertion loss. In the laboratory, we had also tested the case where the two antennas were fed initially in phase, and then out of phase using an electronically controlled phase shifter. This was done in order to improve room coverage, and as a result tag readability, by shifting the nulls of the established standing wave inside the room.

| (a) | (b) | (c) |

Fig. 2. (a) Stick-like USB/UHF RFID reader/writer; (b) RFID enabled plastic identification card; (c) RFID wristband.

The dimensions of the two antennas in each of the rooms were approximately 20×20 cm, whereas the corresponding half-power beamwidth (HPBW) and directivity were 72 degrees (elevation and azimuth) and 7 dBic, respectively (Fig. 3). The maximum VSWR was 1.3 within the bandwidth of interest (865-868 MHz). The two antennas were fed by low loss coaxial cables (heliax) characterized by less than 0.13dB/m attenuation.

The distance from the port to the power splitter was 8 m, whereas the distance from the power splitter to the antenna port was 1.5 m. Thus, the total distance from the reader's port to the antenna's port was approximately 10 m, implying
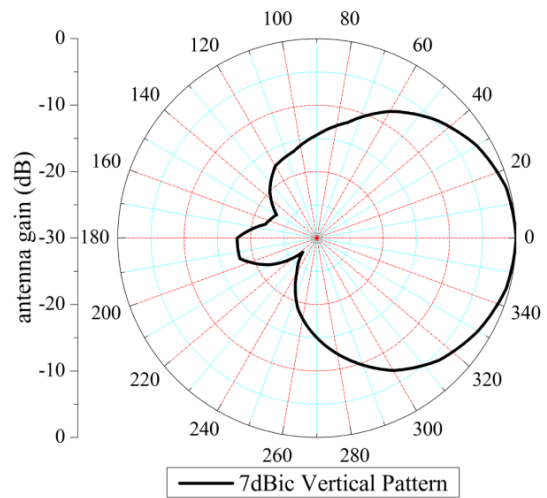

Fig. 3. The H-plane pattern for the wall-mounted RFID Reader antennas used.

an attenuation loss of approximately 3 dB if we consider that the signal will travel twice through the cables, and if we account for the small insertion loss of the splitter and that of the connectors and/or adaptors.

Optimization of antenna position and tilt angle in the presence of lossy walls, floor/ceiling, and patient beds was carried out using an in-house developed ray-tracing code [8], [10] (see Figs. 4-6), which takes into account antenna pattern and polarization, radiated power, multiple reflections, edge diffraction, etc [10]. Alternative models in the literature can be found in [11]-[13]. Extensive results from our work are reported in [8]. In synopsis:

- Single-antenna configurations should be preferred, provided that the radiation pattern of the antenna adequately illuminates the volume of interest (Fig. 4).
- Multiple antenna configurations (fed by the same reader-port) create destructively interfering fields even at the vicinity of their position, thus introducing "holes" of coverage in the volume of interest (Fig. 6). Hence, when multiple antennas are the only choice (due to the inability of the single-antenna radiation pattern to adequately cover the volume of interest), the two antennas should be placed such that their interaction is minimized. A good practice is to place the antennas at close distance (smaller than half a wavelength) and

properly rotate them so that their 3dB beamwidths illuminate different angular segments in the room (Fig. 5).

- Alternatively, when multiple antennas are used, they should be fed through switch-controlled phase shifters so that when a phase shift is introduced at one state of the switch, the "holes" in the room (which were present during the previous state of the switch) are converted to "maxima".
- Another solution is to schedule the transmission of each antenna in time slots so that a single antenna per channel is operational in each time slot.
- Multiple low-cost passive tags could be attached to a target object. It was found that tag polarization diversity or tag spatial diversity increases the percentage of object identification by approximately 10% (Fig. 10).

All simulations were verified by measurements carried out in a "controlled" laboratory environment, where a measurements' grid composed of 120 vertically and horizontally polarized tags was established (Fig. 7). It was found that approximately 93% coverage (at -14 dBm required tag's reception level) could be accomplished by feeding two antennas through a passive splitter, where the two antennas are placed closed to each other and illuminate a different part of the room (Fig. 5). Room coverage may be further improved by using RFID chips/tags with lower sensitivity. Chips with -18 dBm sensitivity are now available in the market [11]. However, some additional losses are expected when the tag is attached to the target object [14]; hence "-14 dBm" was assumed to be the marginal tags' "wake-up" threshold. In addition, a method to acquire power measurements from the tags' grid was put forward [6], [8], exploiting the constant "sensitivity-during-read-threshold" of each tag. Good agreement between the ray-tracing tool and the measurements was recorded [6] (Figs 8-9). Measured tags' polarization diversity gains are presented in Fig. 10. Distributed tag measurements can also be found in [15]-[17].
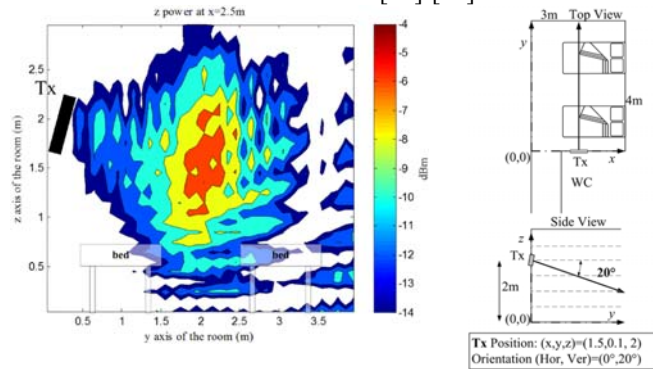

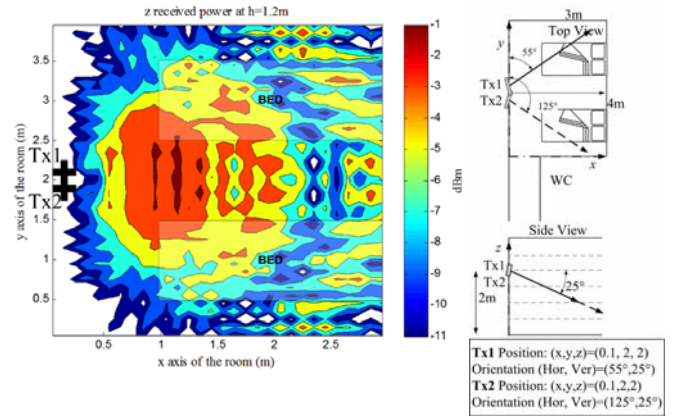**Fig. 4.** Z-pol received power for a single antenna case (x-slice).

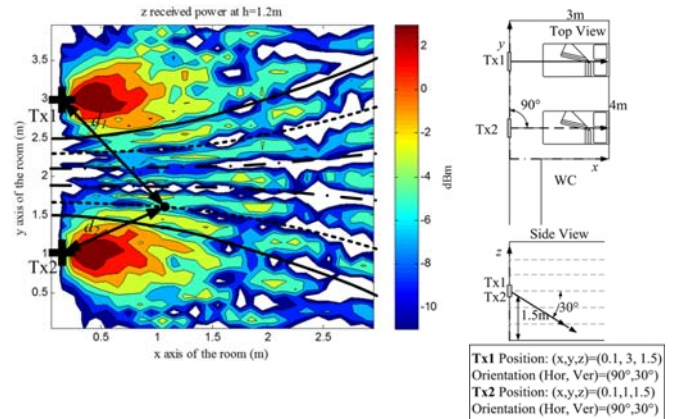**Fig. 5.** Z-pol received power for a double antenna case (z-slice)

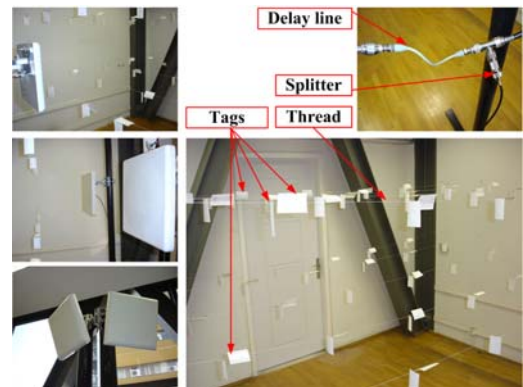**Fig. 6**. Destructive interfering field patterns for a double antenna case.

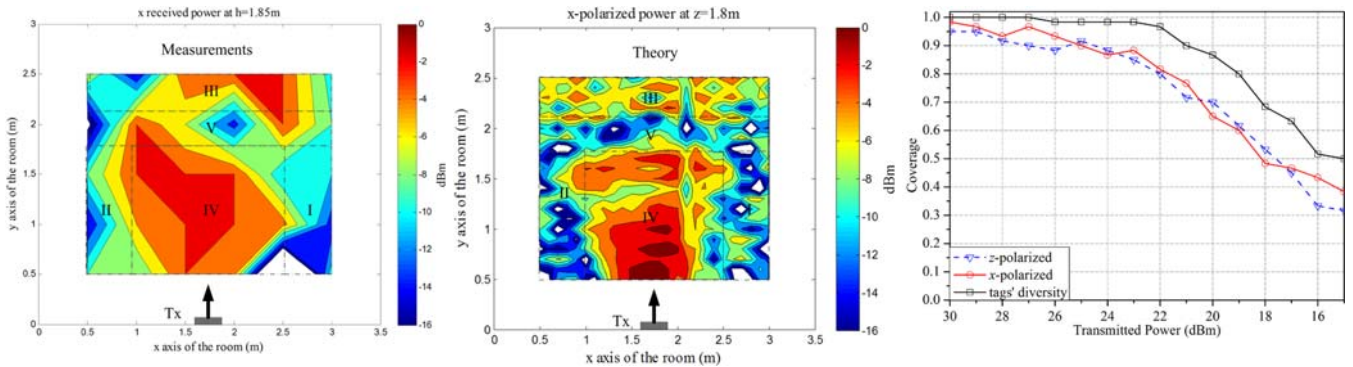**Fig. 7.** Measurements taken in a controlled environment.

Fig. 8. Power measurements using the passive tags' grid (50cm spacing among samples).

Fig. 9. Ray-tracing results for the same configuration (10cm sample-spacing).

Fig. 10. Measured tags' polarization diversity gains.

For monitoring the current stock at all times along with the flow of drugs in and out of the drug inventory cabinet, a single or pair of antennas was installed. An RF port of the stationary RFID reader was allocated for this purpose. Each drug, whether it was powder based or liquid based, was equipped with an inlay RFID tag which was programmed and printed at the pharmacy of the hospital before it was dispatched to the ward. The tags used were 7 cm long and had -14 dBm chip sensitivity. An RFID printer was installed at the pharmacy in order to allow programming and printing of RFID tags on the medicines before dispatching them to the hospital ward. A block diagram of the overall RFID system design, depicting the various hardware components used, is shown in Fig. 11.

Fig. 11. Block diagram of RFID system design depicting hardware components used.

III. System Software Design

The software platform was written for a medical tablet or similar handheld devices such as a Personal Digital Assistant (PDA). This graphical software platform had to interface with the middleware of the USB reader, and that of the stationary reader, in order to extract specific information regarding the tag's ID (e.g. EPC code) or other information stored on the tag. In addition, the interfacing software had to have the capability to communicate with the reader's middleware in order to write information on the tag. Other settings are possible through this interfacing software such as controlling which port to transmit at a given time, the level of transmitted power, the allocated frequency channel, and the duration of interrogation. The source code was written in different programming languages including C++, C, and C#.

The software that provides interfacing to the middleware is totally transparent to the user. The user interacts only with the application part of the software which is fully graphical. This Graphical User Interface (GUI) is easy to use by medical staff and hospital administrators. Fig. 12 shows the LOGIN screen of the GUI depicting a NURSE account, a DOCTOR account, and an ADMIN account. These accounts have different privileges and capabilities. For example, using a DOCTOR account one may prescribe drugs electronically, or change a prescribed dosage of a given drug, or view the entire medical history and profile of a patient. Using a NURSE account, one may view the assigned tasks of the day for a given patient, view basic information regarding patient profile, and execute routine daily tasks such as taking patients' temperature and pressure measurements. Using an ADMIN account, one may add a new in-hospital patient, delete a patient, add a new drug/asset to the list of drugs/assets in the database, add/delete a doctor/nurse account, etc.
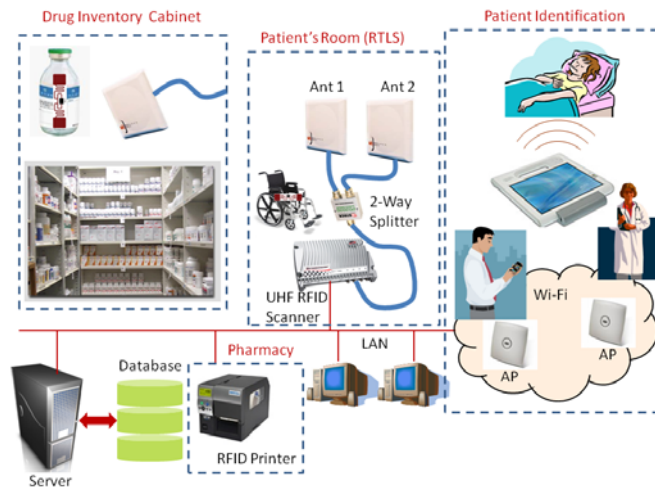
In addition to the account icons, there are other icons part of the front view of the GUI which are related to inventory control, RTLS (Find Items), programming and printing of tags for medical assets and drugs, and logout. For the inventory control, once the corresponding icon is activated, the user enters the screen shown in Fig. 13. By pressing the 'Connect' button on the top left corner of the screen, the tablet connects to the RFID system empowering the scanning capabilities of the GUI. Pressing the 'Scan' button, the stationary reader launches a signal to the RF port covering the inventory cabinet for a pre-assigned time interval. The antennae inside the inventory cabinet radiate for a short period of time (~5 seconds) and capture the backscattered response. The corresponding middleware decodes the signal and isolates useful information (e.g. EPC codes, etc.) which is then passed to the interfacing software and to the application GUI. This information is tabulated and shown in a table as the one depicted in Fig. 13. Double-clicking on a specific drug in the list, additional information pops out in a separate window. This information includes expiration date, place of origin, manufacturer, patient's name drugs are assigned to, etc. Thus,

the system provides ways to avoid medical errors such as administering the wrong medicine to the wrong patient, administering a drug that has already expired, or facing a run-out-of-stock situation without notification. The scanning process of the entire inventory cabinet can take only a few seconds, thus avoiding labor intensive tasks for stock taking. The list of drugs, as shown in Fig. 13, can be tabulated according to drug type, expiration date, quantity, manufacturer, etc.

The RTLS (Find Items) icon can be activated by all medical staff in search of medical assets (e.g. wheelchairs, infusion pumps, computer monitors, etc), patient files, and high-value equipment. When the 'Find Items' icon is activated, the GUI launches the screen shown in Fig. 14 where it depicts the top view of the hospital ward. Depending on the particular item one may be searching for, s/he may activate one of the icons shown at the bottom of the screen. In the case illustrated in Fig. 14, the user had activated the 'Wheelchair' icon and, in a very short amount of time, the system responded with one wheelchair in *Room 33* and two wheelchairs in *Room 35*. Using this facility, the nursing staff is not wasting valuable time to wander around the hallways of the hospital ward in search of wheelchairs or other type of assets. This effectively saves on labor and running cost for the hospital and boosts productivity and efficiency at workplace.

The other two icons in Fig. 12, which are related to the programming and printing of tags for assets and drugs, are often used by the administrator or the pharmacist. For this purpose, there is a dedicated RFID printer in the pharmacy of the hospital that has been interfaced with the rest of the system and has been programmed to read the EPC code from the next available tag in queue. Once read, the EPC code is inserted into the system database and assigned to a specific drug or asset. The system allows the user to store auxiliary information in the tag and even print information on the label itself. This facility allows for a convenient, easy, and quick way of programming and assigning tags to either drugs or assets.

During a routine round at the hospital ward, a nurse is equipped with a tablet PC connected to the WLAN. A stick-like RFID reader is attached to the USB port of the tablet enabling identification of a patient with an RFID badge or wristband. The nurse logs into his/her account using a username and a password. Once in the system, s/he activates the 'Scan' button and reads the RFID tag of the nearby patient. Readability can be achieved from a distance smaller than 80 cm. Once the patient is identified, his/her basic medical information, including a picture, name, medical condition, etc, is automatically uploaded on the front screen of the tablet. This process always ensures error-free identification of patients.

Fig. 12. Login screen of the RFID enabled healthcare management system.
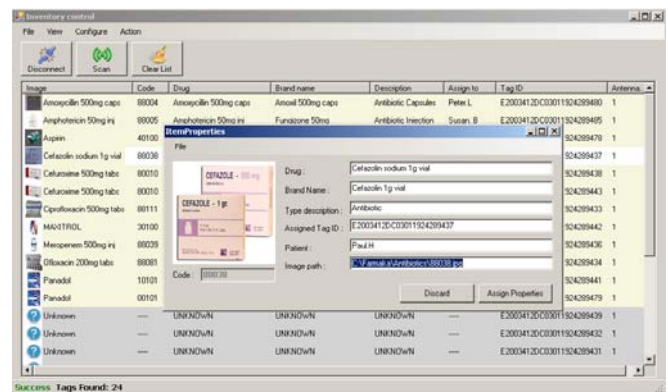

Fig. 13. Drug inventory screen: Drugs identified inside the inventory cabinet are tabulated after the SCAN icon was activated. Additional information concerning a particular drug can be provided by double-clicking on the drug name.
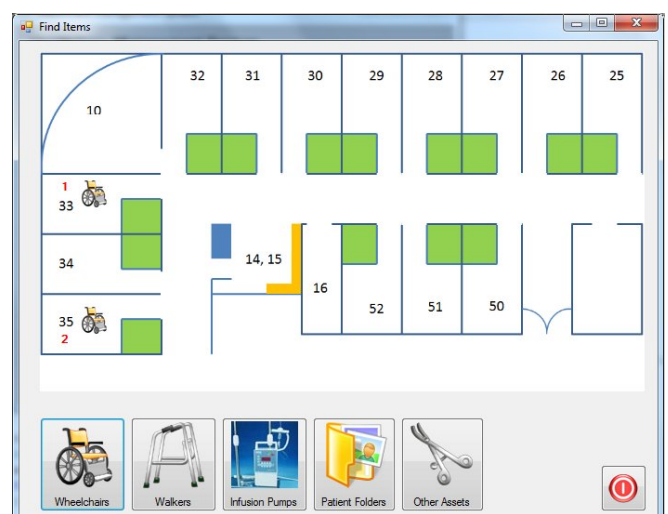

Fig. 14. RTLS screen showing the top view of the hospital ward. Pushing the 'Wheelchair' icon indicates that there exist one wheelchair in Room 33 and two wheelchairs in Room 35.
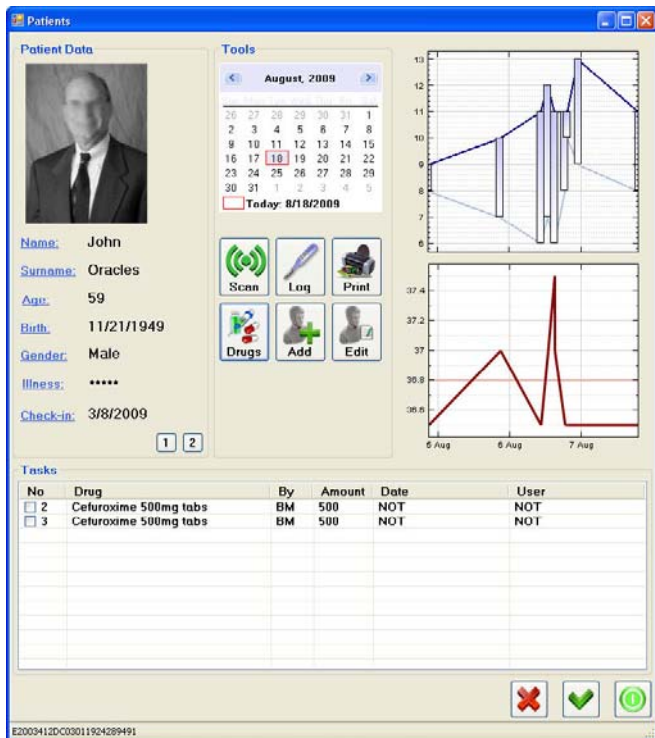
Fig. 15. Nurse account once patient identification is achieved.

A typical view of the nurse account, once patient identification is achieved, is depicted in Fig. 15. At the bottom of the screen, the nurse can visualize all scheduled tasks for the day, whether that is drug administration, radiotherapy, physiotherapy, etc. Once a particular task is completed, the nurse has to check the corresponding box which automatically records the time, date, and name of the person who completed the task. This provides accountability and traceability in case of a medical mistake or malpractice. On this screen, the nurse may choose to view the patient's profile or doctor in charge. In addition, during the visit, the nurse may perform temperature and pressure measurements which are recorded on the system allowing doctors to monitor the patient's progress remotely.

IV. SYSTEM INSTALLATION & EVALUATION

The RFID system, as described in the previous two sections, was installed at the BOCOC in Nicosia, Cyprus. As this was a pilot project with limited funding, the system covered three patients' rooms only plus the drug inventory cabinet near the nursing station. The dimensions of each of the patients' room were 6×3 m. Two circularly polarized antennas, as shown in Fig. 16, were installed side-by-side in each of the three rooms via a low-insertion loss, bi-directional, 2-way splitter/combiner connected to one of the four available monostatic RF ports of the UHF/RFID scanner. Once activated, the antennas radiate in space for a very short period of time which was set to 5 seconds. The software platform allows for the interrogation time to change accordingly. The scanning of the antennas is initiated by pressing the 'Scan' button of the RTLS screen of the software application. This

button is activated when in search of patient files and medical assets such as wheelchairs, infusion pumps, computer monitors, etc.
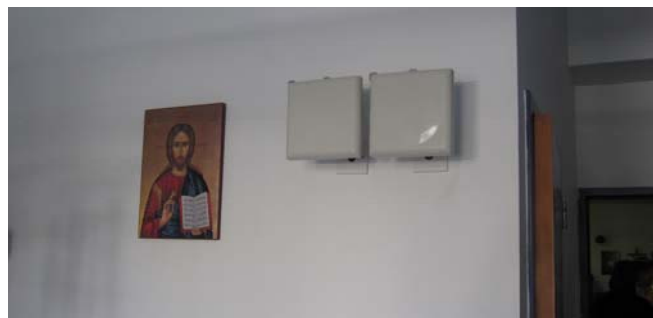

Fig. 16. Side-by-side antennas providing EM coverage inside a patient's room; tilting of the antennas in azimuth and elevation planes can be adjusted.

Measurements were conducted in the three patients' rooms in order to evaluate EM coverage and tag readability. In each of the rooms, there were two patient beds, chairs, and medical equipment (e.g., computer monitors, infusion pumps, etc). The measurements were performed in the presence of the two in-hospital patients, two close relatives of them, and two members of the research team performing these measurements. It is also important to emphasize here that the precise position and orientation of the two antennas in the rooms did not fully agree with the initial design proposed by the research team mainly due to restrictions imposed by the hospital administrators during the installation of the system. Nevertheless, we proceeded with the installation and testing of the system despite of these modifications. Of great importance was the fact that measurements of EM coverage were performed in a realistic hospital environment as opposed to a laboratory. EM coverage measurements in one of the three patients' rooms are shown in Fig. 17 for a group of 20 closely spaced RFID tags placed on a cardboard box (see Fig. 18) oriented either vertically or horizontally. We did not expect to obtain readability when the cardboard box was located close to the entrance of the room due to the orientation and the mount position of the antennas. For this reason, no measurements were performed near the entrance of the room. Mounting the antennas on the opposite wall would have been a much better choice, however, that was not feasible. As seen from Fig. 17, the maximum tag readability observed corresponds to reading 20 tags (100%), and the lowest readability observed corresponds to reading only 11 tags (55%). The percent readability is shown in red, whereas the height of the cardboard box is shown in black. On the average, for vertically oriented tags, readability was found to be 88%, and for horizontally oriented tags, readability was found to be 83%. The sensitivity of the chip used in the inlay tags was -14 dBm. As mentioned before, object identification can be further improved by using spatial or polarization diversity of tags or by utilizing tags with higher sensitivity.

Besides tag readability inside a patient's room, measurements were conducted near the nursing station in order to evaluate the ability of the system to read and uniquely identify drugs stored inside the inventory cabinet shown in Fig. 19. A pair of side-by-side circularly polarized antennas

was installed on the top of the cabinet pointing toward the interior. For powder-based drugs, like Vancomycine shown in Fig. 20(a), and when the tag was facing up toward the antennas (face-up), readability was achieved everywhere in the cabinet; however, when the tag was facing down, readability was achieved only when the container was placed on the upper two shelves. The reason for the failure to read the tag, when the drug was placed face-down on the bottom two shelves, is due to the fact that the tag was in direct contact with a liquid container.

Fig. 17. Measurements for tag readability inside a patient's room when tags are oriented vertically or horizontally with respect to the floor.

Fig. 18. Cardboard box with 20 aligned inlay tags attached.

In the case of an RFID tag attached to an IV bottle, having a diameter of 7 cm and a height of 12 cm, as shown in Fig. 20(b), the observations were not the same as the observations recorded for the powder-based drug. The tagged liquid bottle was placed inside the cabinet starting from the upper shelf all the way to the bottom shelf. The bottle was standing upright, as shown in Fig. 20(b). Readability of the tag was achieved only when the bottle was placed on the upper two shelves. The presence of liquid in direct contact with the inlay tag antenna obviously deteriorates the established link budget. A possible explanation is the detuning of the input impedance of the tag antenna thus affecting the reflection coefficient at the terminals between the antenna and the chip. Another possible

explanation is the dissipation of a significant amount of incident power inside the liquid. Now, when the IV bottle was placed on the bottom shelf, the tag was no more visible by the system, thereby concluding that a significant amount of radiated power was absorbed and dissipated by the lossy liquid. Thus, the amount of energy captured by the tag antenna, and eventually delivered to the chip, was not sufficient to power up the device. Readability was achieved everywhere inside the drug cabinet only for the case where the tag was placed on the bottleneck of the IV bottle, as shown in Fig. 20(c). In this case, the liquid was not directly beneath the tag. As a result, the resonant frequency of the tag antenna was not greatly affected by the presence of liquid. The same experiment was performed with an even larger IV bottle and readability was again not affected.
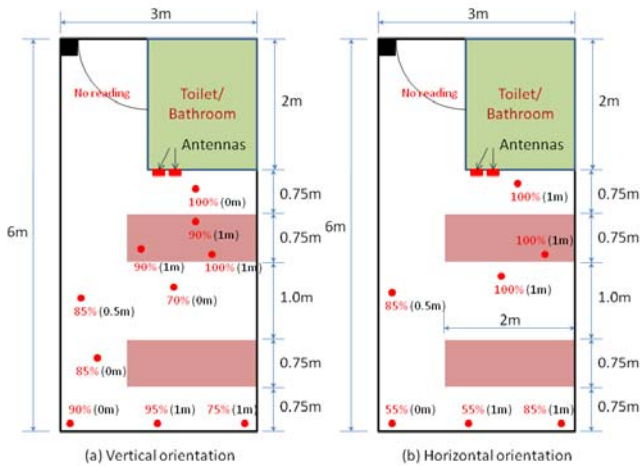

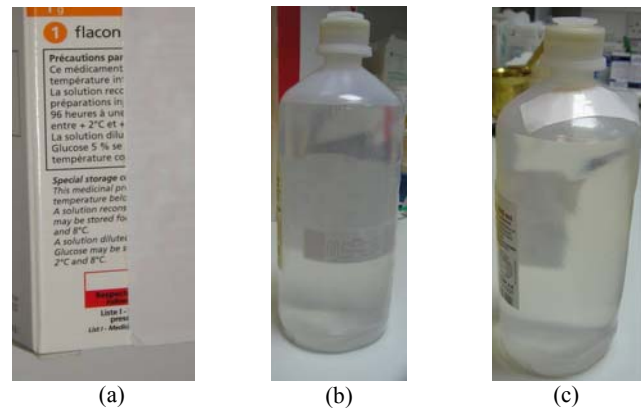**Fig. 19.** Interior of drug inventory cabinet.

Fig. 20. (a) Powder-based drug; (b) Liquid-based drug (IV bottle) with tag on the side; (c) IV bottle with tag on the bottleneck.

Another type of drug that was considered was a flat container (bag) of Sodium Bicarbonate (100 mg) shown in Fig. 21(a). The RFID tag was first placed on the plastic edge of the bag, as shown in Fig. 21(a), and it was tested for readability when placed inside the cabinet. Readability was achieved only for the top two shelves. When the tag was placed in the middle of the bag, as shown in Fig. 21(b), this particular drug was not readable even when placed on the upper shelf.

Fig. 21. RFID tag placed: (a) on the plastic edge of the bag; (b) in the middle of the bag (liquid underneath).

Identification of patients in the hospital ward was tested using RFID-enabled medical tablets. The medical tablet is lightweight and easy to use by medical personnel. It is equipped with a clip-on accessory providing USB and Ethernet access. A USB stick housing a UHF RFID scanner was attached to the USB port. An interface was written to provide communication between the middleware and the software application (GUI). Through the GUI, a doctor or nurse can activate the external USB stick by simply pressing the 'Scan' button (See Fig. 15) of the patient identification screen. The scanner launches an RF wave initiating a communication between the scanner and an RFID tag within a radius smaller than 80 cm. We tested the system using a variety of UHF wristbands available in the market but readability was very poor. Specifically, we were not able to identify patients at distances larger than 5 cm. The reason is possibly attributed to poor matching between the tag antenna and the chip. Then, we used RFID tags in the form of inlays attached to the patient's plastic ID card (badge) and the results were excellent. The system was able to identify a patient from a distance of 80 cm. Readability was sought everywhere in the ward as there was sufficient coverage by the wireless access points. Tag readability was compromised only in cases where the USB stick was loose at the port connection. Having an external USB stick-like scanner at the port should not be a permanent solution.

V. CONCLUSION

A RFID system based on passive UHF technology was designed, installed, and tested at a realistic hospital environment. A software application was written for a medical tablet to provide a user-friendly interface between the user and the system hardware/middleware. All three main tasks of the system performed adequately. Of special importance to the nursing staff was the RTLS part of the system. Locating tagged objects in the hospital ward saves valuable amount of time and promotes productivity and efficiency at workplace. Additional effort should be placed by researchers in optimizing electromagnetic coverage and tag readability in indoor environments, especially in the presence of liquid containers and metallic objects [20]. Our experiments have shown tag readability on the order of 88% for vertically oriented tags, which is considered satisfactory.

The pharmacists were enthusiastic with the use of drug inventory control and monitoring as they were now able to automatically check the inventory cabinet and perform stock taking in real time. Even though this system worked quite well for powder-based drugs, significant problems with readability were observed in the case of liquid bottles inside the cabinet. Apparently, when the tag is in direct contact with the liquid, the reflection coefficient at the chip's terminals is severely affected thus reducing the input power to the chip. Use of near-field tags along with near-field antennas can improve readability of liquid products only at short distances (e.g. on a conveyor belt) [21].

The doctors preferred the patient identification platform; however, not all the doctors were eager to use it. This platform provided means to reduce patient mix-up errors or errors related to drug administration. The patient identification system worked very well, and it was proven quite useful as it provided automatic patient identification, secure exchange of information with the server, automatic uploading of patient data and medical history, accountability for nursing activities in the ward, electronic prescription, etc.

Despite the aforementioned challenges still to overcome, we believe that passive RFID technology in the UHF range has a bright future in healthcare applications as it provides significant advantages over other frequency bands (e.g., HF) or other technologies (e.g., NFC, barcodes). In addition, the foreseen benefits from introducing this technology in the healthcare sector certainly outweigh the initial investment cost and time required by someone to get acquainted with new processes and policies.

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