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RFID Modeling in Healthcare

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1. Introduction

Increasingly, healthcare management systems include investment in and implementation of technology to track the status and movement of various entities within the healthcare environment, including patients, healthcare workers and physical assets. This is often a means of understanding patient flow, controlling inventory, tracking equipment usage, and thereby (ideally) assessing efficiencies in order to optimize resources and processes within that environment (Wang et al., 2006). The focus of this chapter is to highlight the contributions of RFID systems modeling, particularly in relation to an understanding of the nature and extent of system error that is often overlooked experientially. The healthcare environment was chosen as it is an increasingly complex and interesting application area for RFID, and in which a wide range of RFID-based applications and devices already exist and can be envisioned for the future. The insights gained through modeling provide a complementary set of data to those gained from the experiential knowledge of performance in existing installations. To that end, this chapter focuses on a case study of an agent-based model (ABM) of a hospital emergency department (ED), with extensions to modeling the provisioning of a real-time location system (RTLS) using RFID for patient tracking.

To contextualize this work, Section 2 reviews conventional and emerging RFID applications in healthcare. Section 3 introduces the agent based modeling technique, invoked to investigate system performance in an application for RFID-enabled patient tracking within an ED. The ABM was developed as a decision support tool oriented towards optimizing RFID placement (minimizing uncertainty) for an actual ED where healthcare managers are considering the deployment of such systems. Section 4 outlines the ABM simulation results, with a particular focus on the nature and extent of system error and uncertainty – both spatial and temporal – that modeling illuminates. Section 5 discusses implementation strategies for an RFID RTLS system reflecting a Service Oriented Architecture approach that leverages existing software systems and focuses on being IP-centric and application- and device-agnostic.

2. RFID healthcare applications and patient tracking systems

The current scope of RFID technology in healthcare includes conventional as well as emerging 'smart' RFID devices and applications. The overall objective of RFID applications in healthcare is to automate manual processes as well as to reduce the time required to track

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and locate assets, including vital supplies and people and thereby resulting in institutional and productivity gains (Kanyuk & Young, 2004). Ultimately, RFID applications in healthcare can support service providers in decision making functions and arduous tasks typical within a complex clinical environment. Over the range of applications, RFID in healthcare generally shows capacity to i) identify, track, and locate patients, healthcare personnel, medical files, medical equipment, medical supplies, medications, and laboratory and pathology samples; ii) detect incorrectly packaged medications or supplies and doses; iii) institute systems to recall counterfeit or contaminated medications and supplies; iv) correctly identify and locate potentially 'misplaced' surgical instrumentation – even those accidentally left within a patient during a surgical procedure; v) corroborate medical supply and surgical instrumentation sterilization; vi) ensure safe and proper handling and disposing of bio-hazardous materials, expended medications, medical supplies and devices, and waste; vii) and, even 'confirm' actual anatomical locations for surgical procedures. Thus, at the patient point of care (POC), RFID can serve to correctly identify patients to receive and care providers authorized to deliver a prescribed medical treatment or procedure. Overall, in the healthcare sector there are many emerging RFID inventions that can offer drastic improvements in processing times associated with medical records retrieval, efficiency of service and reliability of medical diagnosis, dispensing of medications, and personnel management (Solanas & Castella-Roca, 2008; Wicks et al., 2006). The overall goal of these technologies is to facilitate improvements to patient safety and quality of care, and to do so in a cost effective manner.

First-generation RFID applications have been in commercial use for well over 20 years. These conventional applications in healthcare are primarily based upon identification, for example technologies and methodologies for improving patient POC and reducing errors based on barcodes and RFID (Rao & Dighe, 2004; Bearing-Point Inc., 2006; Podaima & McLeod, 2006). In general, conventional applications enable systems to be built around inventory tracking and control. Extensions include pharmaceutical supply chain inventory and tracking for medical reconciliation. Tied into a hospital management system, they hold considerable potential to reduce adverse drug events at the patient POC. This is accomplished through corroboration of the patient ID with the drug prescribed by the physician. These technologies carry increasing potential as the supporting electronic technology improves and connectivity protocols become standardized (Dubois et al., 2001). One of the limitations with early adoption of both RFID and barcodes is that they are inherently submissive, allowing for identification with little or no support for interactivity and automation.

Second-generation or 'smart' RFID-enabled healthcare solutions offer an expanded functionality beyond conventional RFID tagging alone. While conventional RFID is typically reserved for supply chain management, incorporating identification, asset tracking and locating (Glabman, 2004), smart RFID-enabled devices incorporate the functionality of control – both sensor and actuation – facilitated by advancing microelectronics technologies such as system on chip (SoC). Within this expanded capability, applications incorporate an RFID enabled electromechanical lock or latch used in combination with a pervasive health informatics platform. In a medical compliance configuration, this serves to mitigate against adverse drug events and can be implemented in smart syringes, smart couplers, smart medical containers, smart pumps, smart clamps, smart valves, smart pipettes, and smart bandages, for applications requiring the proper identification and corroboration of IV

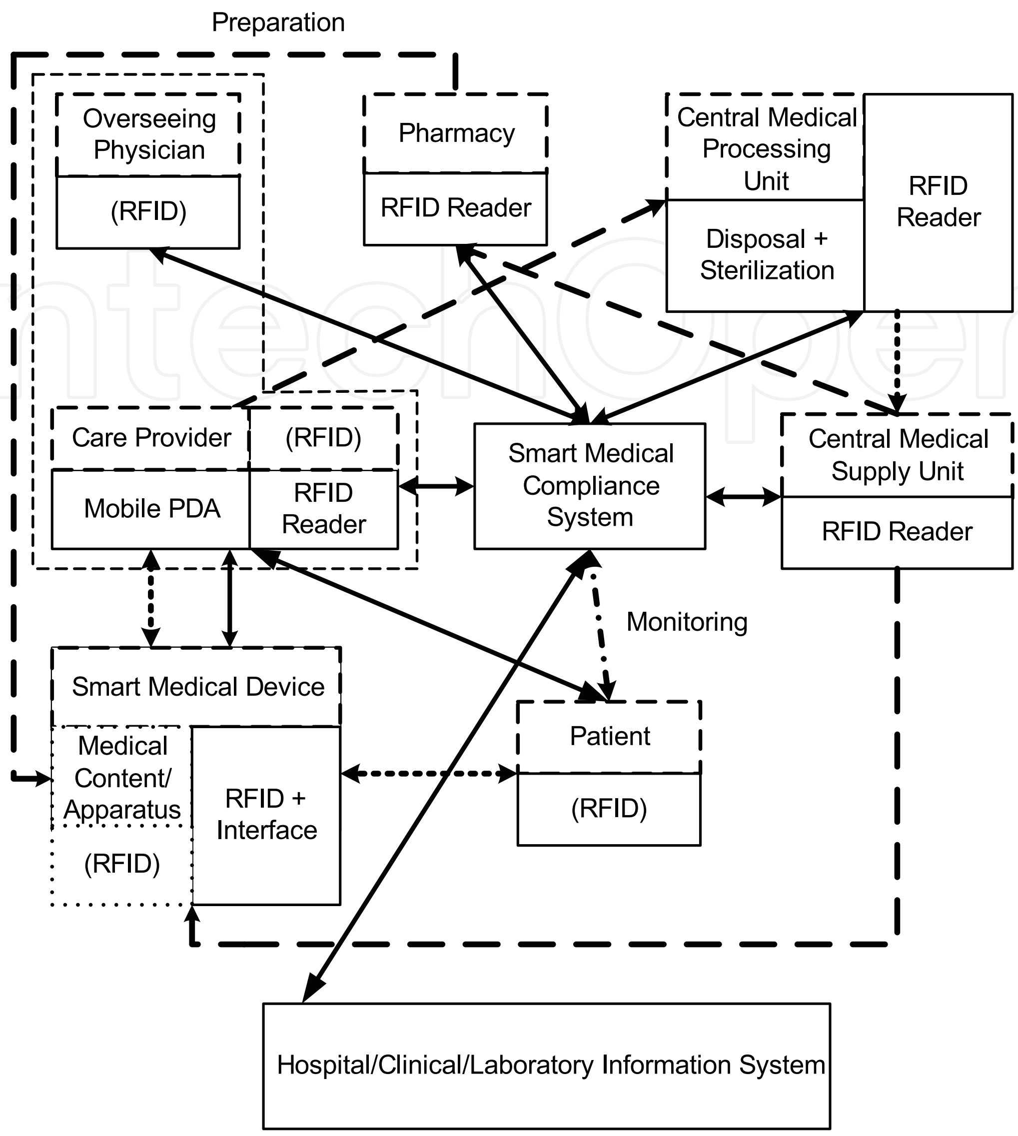

Fig. 1. Medical compliance platform – POC interaction components

infusion (smart pumps), and medication dispensing (Podaima, 2007). The RFID tags on these devices can be either active or passive, and the control and communication can be derived from the interaction of an RFID reader and tag in conjunction with the associated electronics and overseeing medical information management system. Smart RFID also introduces novel designs for integration with evolving and legacy POC systems. Figure 1 illustrates a conceptual overview of the POC interacting components within the medical reconciliation and compliance platform.

Smart RFID with its enhanced functionality lends itself to improved fail-safe or 'intelligent' medical devices, medical compliance and reconciliation systems encompassing medication prescription, transcription, administration, and pharmacological preparation, and physical and biological sensor-based functional-monitoring modalities. The benefits of smart RFID are compounded when used in conjunction with conventional RFID tagging (e.g. RFID badges, RFID wristbands) for identifying patients, healthcare providers, and medical supplies and equipment. For instance, a smart RFID-enabled hand washing hygiene surveillance and compliance system implemented across an entire healthcare facility can be a most important tool in preventing the spread of infection. This application is representative of the kind of capabilities of enhanced smart RFID-enabled devices, as it can reduce the risk of widespread (nosocomial) infections causing harm or even death due to staff and visitor non-compliance.

As another example, a Smart Coupler incorporating the functionality of smart RFID-enabled fail-safe locking technology is manufactured by Colder Products Inc. (Bacheldor, 2006). The two-piece smart coupler consists of a male and female sub-miniature plastic connector containing an integrated RFID tag and RFID reader, respectively, typically used for connecting medical and surgical equipment, including blood-pressure cuffs, blood analyzers and analytical instruments, and IV infusion bags. When two pieces of the connector are joined for coupling, the RFID reader scans the tag. If there is a mismatch or incompatibility, the error could trigger an alarm and/ or the completely disable the coupling function. In addition to this smart technology ensuring that the equipment is hooked up properly, it also ensures that healthcare providers aren't reprocessing and reusing devices that are actually intended to be disposable. By programming the smart coupler system (RFID reader) via a computer interface, application specific data and rules can be customized for the particular application.

A further example of a smart RFID application in healthcare is the Smart Syringe currently under development by Virtuistix Inc. (Podaima, 2007). The Smart Syringe extends the basic injection principle of a standard syringe in that it offers much greater capability and purpose via integration with an RFID-enabled capability. Thus, a Smart Syringe has a bi-directional communication channel along with a microcomputer interface. The capability therein incorporates a controller that authorizes the operation of a manual or automatic mechanical injection plunger with a lockable-latch or pinch-off regulating mechanism, thereby modulating the flow of fluid through a syringe. The Smart Syringe incorporates an RFID tag and accompanying interface (*in situ* and/ or external) in a method and system to control the mechanical operation of a plunger either i) manually enabling or precluding an instance of user operation of the syringe plunger regulating mechanism, or ii), automatically enabling or precluding an instance of power assisted (e.g., electromechanical) operation of the syringe plunger regulating mechanism. Hence, in addition to facilitating flow by activating a syringe plunger regulating mechanism (opening, closing, or modulating), this smart syringe assembly incorporates a lockable-latch which will prevent unauthorized, erroneous, or inadvertent operation. In the field, information will be available as to the status of operation (metrics, performance), maintenance, and serviceability (replacement).

The RFID-enabled Smart Syringe can be identified with an RFID reader juxtaposed with a mobile or handheld computer (computer on wheels or personal digital assistant), or a stationary communicating computing device. In this configuration, the RFID reader can thereby be used to interrogate the smart syringe status as well as identify patient (via RFID wristbands or badges), healthcare provider, and other medical supplies and equipment used in the treatment modality. The handheld computer can provide on or off-line audio and video status as to the authentication and compliance of the medical procedure or treatment in real-time. Thus, the communication and electromechanical control can be derived from the interaction of the RFID tag (and associated electronics) and the RFID reader and, in some instances, an overseeing healthcare information management system. Upon identification, corroboration, and authentication among patient, care provider, and medication preparation in the Smart Syringe, the interrogating RFID reader could be used to activate or preclude the Smart Syringe latch and/ or plunger regulating mechanism according to the prevailing medication compliance protocol.

Future smart RFID-enabled medical devices will extend well beyond traditional uses, and as such will incorporate various sensors and actuators, likely to be widely available as implantable devices (Ross, 2004). The integration of RFID with bio- and chemical sensors is also of great interest, in that the combination can be used to create new devices for both diagnosis and even treatment (e.g., smart bandages) to function in areas previously impracticable. These sorts of hybrid RFID devices can be used practically and robustly – both *in vitro* and *in vivo* – and have far reaching clinical efficacy. Blood glucose monitoring is one example of an implantable RFID SoC device that can be used by diabetic patients without the requirement for taking blood samples subcutaneously several times per day. Intestinal and esophagus monitoring with pH and temperature sensors also fall into the same class of device; they offer a minimally invasive means of biopsy and diagnostics, facilitated as a direct result of venerable RFID-based SoC technology.

It should be recognized that both conventional- and smart-RFID are not panaceas to solve all healthcare management issues, as they have current technological limitations characteristic of many new technologies, and are fraught with privacy and security concerns. Additional considerations include the reuse (i.e., sterilization) of devices, which implies an additional constraint that may require the device to be subject to temperature, chemical, pressure, and/or electronic processes not otherwise needed in less sterile environments. As with other medical devices, Clinical Grade Smart Medical RFID-enabled devices will be required to meet the stringent standards and guidelines of various governing bodies and institutions of the healthcare industry. These include mandates regarding security, integrity (encryption), and privacy. Clinical grade RFID-enabled devices will also be required to meet rigorous EMI and EMC (electromagnetic interference and compatibility) guidelines (Ashar, 2007; Witters, 2009). Thus, smart RFID-enabled medical devices come with an associated overhead, but are not superfluous in deployment, and can be used within the framework of an engineered POC system (Ehrmeyer et al., 2005; Roberts, 2005). Currently, the capacity exists for seamless integration with purposeful function, and an evolutionary path to improved overall medical compliance.

Over the next several years, we expect to see a significant push for improved healthcare services and medical records adoption demanding quicker, better, and cheaper point of care and clinical biomedical testing and diagnostics. To fulfill this need, opportunities will continue to emerge for both conventional- and SoC- RFID-based smart healthcare technologies to play a viable role in delivering on this promise, toward the ongoing goal of improved patient safety and quality of care.

While this discussion demonstrates an increasing range and variety of RFID applications and devices prototyped and implemented in healthcare settings, much less work has been done on *modeling* RFID systems in healthcare, in order to gain insights into implementation parameters of RFID applications. In the following section, a case study is presented which investigates the modeling of a conventional RFID application – that of patient tracking in an ED – with a particular interest in the nature and extent of uncertainty and error in the system, which is often overlooked in real installations and real data.

3. Case study: agent based modeling of RFID placement for patient tracking in an emergency department

3.1 Introduction

Evolving RFID RTLSs are meant to augment and/or automate the existing data capture (electronic records systems) in place in many healthcare institutions. A typical patient trajectory capture system may include the collection of time of arrival, time of triage and registration, time and duration of treatment including specialty consultations, and time of discharge from the ED. In some cases, data are entered by healthcare workers for multiple patients in aggregate when there is a break in the workflow. As such, there may be considerable uncertainty associated with the data themselves, making it difficult for policy-makers to make statistically verifiable decisions as they attempt to optimize patient access and flow through the healthcare facility. In this context, RFID systems offer a complementary and more automated means of data collection. However, critical issues are again associated with uncertainty and consequent inferencing required to remove ambiguities in the data.

To preface a discussion on error and uncertainty in RFID systems, a brief discussion of the system hardware is introduced. For our purposes, RFID systems are considered to be tag-and-reader systems, comprised at minimum of a number of tags and at least one reader. These RFID systems operate over a variety of frequency ranges and with a variety of complexities associated with the tags as well as readers. In general, a tag is associated with an asset or patient and the reader is associated with a location in the physical environment. The tag can be either passive or active, the latter requiring a battery allowing it to power a transponder and allowing it to be interrogated by a reader. A passive tag obtains its power from the field of the reader, allowing it to effectively "transmit" its identification back to the reader (Finkenzeller, 2003). Passive tags are modeled in this study.

Several sources of uncertainty and error become immediately evident, yet are often overlooked by users. First, once a tag is read, it is primarily a proximity measure, meaning the tag is somewhere within the proximity of that reader. The low frequency passive tags (<20 MHz) use inductive coupling as opposed to propagating electromagnetic radiation, and as such are typically limited to fairly close proximities (~1-2 m). As a consequence, when attempting to create a patient trajectory through a healthcare facility, time-stamped historical data are required and rules of inference are used to estimate a patient's approximate location. Second, a particular reader and tag system will have time-varying non-isotropic capture areas, impeded by distance and other objects in the surrounding area. Third, in the case of the passive tag with virtually no processing power, a reader may read a tag at apparently random intervals or may not read the tag at all, depending on tag orientation and its environment. A fourth issue is interference, where closely-spaced readers interfere to the point where both readers fail to read a tag that passes through or stays within the interference zone. The problematic case is the lack of a read (missed read) by one or both readers. In a study estimating service queue lengths using RFID, Sanders et al. (2008) highlight the extent of uncertainty inherent even in a straight-forward RFID RTLS application.

While both passive and active RFID tracking technology will continue to evolve, and uncertainties in operation and quality will be mitigated, these uncertainties will likely never be completely eliminated. As such, modeling plays an important role in optimizing the implementation of any RFID RTLS patient tracking system. The next section overviews the simulation environment developed for planning and managing a RFID RTLS system.

3.2 Agent based modeling

Agent based modeling has emerged as a simulation technique which attempts to model a system in as much detail as available or as possible. ABM is systems modeling, approached from the ground up or from the perspective of its constituent parts, in order to build an aggregate picture of the whole. Systems are modeled as a collection of agents, their individual behaviours, and their interactions. Agents are autonomous decision-making entities (generally used to model human beings, but can also include inanimate objects) able to assess their situation, make decisions, and compete with one another on the basis of a set of rules. ABM's conceptual depth is derived from its ability to model emergent behaviour that may be counterintuitive or, at minimum, its ability to discern a complex behavioural whole that is greater than the sum of its parts. ABM provides a natural description of a system that can be calibrated and validated by representative experts, and is flexible enough to be tuned to high degrees of sensitivity in agent behaviours and interactions. ABMs are particularly well suited to system modeling in which agent behaviour is complex, non-linear, stochastic, and may exhibit memory or path-dependence (Bonabeau, 2002).

A deterrent to the acceptance of ABM is that, as a technique, it does not lend itself to sensitivity analysis or the modeling of steady state phenomena without a potentially unrealistic number of simulations and substantial statistical analysis being undertaken. Although we agree with that position in general, we also argue that the advantages of ABM complement other techniques. In particular, there is a significant body of literature on mathematical modeling techniques applied to healthcare management, which can be complementary sources of data and cross-validation to ABM (Karnon et al., 2009).

ABM also provides one of the most useful tools available in terms of knowledge transfer and requirements capture, independent of whatever other techniques may be also employed. An ABM has an as close as possible correspondence to the problem as understood by both the practitioner as well as the ABM implementer. An ABM models emergent complex behaviour by specifying rules for simple underlying interactions between agent entities. As such, the resulting model closely resembles the system description, which could come from business rules or some other description by stakeholders who need not be overly familiar with ABM itself.

Many ABMs are developed to gain a better understanding of operations through the use of what-if scenarios. An ABM initially developed for improving patient access to healthcare (Mukhi & Laskowski, 2009; Laskowski et al., 2009) is extended here to allow modeling a RFID RTLS augmented ED, with the objective to gain insights into the nature of error and uncertainty associated with patient tracking. Of primary interest to a RFID RTLS is the accuracy and precision of patient trajectory through the ED. As each agent behaves in an autonomous fashion under the control of the simulator, an exact trajectory is recorded for each patient, which is then available for comparison and validation to trajectory data captured via the RFID RTLS model.

The basic model allows for various configurations, including provisioning the number of healthcare workers (HCW), the number and characteristics of patients, as well as the topography of the ED. Operational parameters in the ED include registration, triage, waiting and treatment areas. The ED floorplan used here closely resembles that of a large, acute-care, metropolitan hospital (Health Sciences Centre in Winnipeg, Manitoba, Canada), although tailoring of floorplans is possible. A schematic of the ABM at an instance of time is illustrated in Fig. 2. In the figure, patients and HCWs are illustrated within the ED with different icons for healthcare workers, and patients at various levels of acuity. This representation also provides a visual animation as the simulation progresses. In effect, the animation is a tool used to transfer information between practitioners and modelers, whereas the extensive collection of data for statistical analysis proceeds without any type of visualization.

The RFID RTLS environment allows for the overlaying or placing of RFID readers which serve as inanimate agents within the ABM. Reader placement can be engineered, or simply distributed in a somewhat systematic manner. For the purposes of this type of simulation, the latter is used to allow for placement roughly based on the density of readers with a specified granularity. In practice, actual reader placement would be subject to access, mounting, and functional constraints, with read patterns also modified as a consequence of the local environment (walls, furniture, equipment, required clearances, as well as people, the latter being time-varying). Tag collision is not considered in this simulation; it is assumed that over the duration of tags being within a reader's range, any colliding or interfering tags would be resolved in a time period considerably shorter than the tags traversing the reader. The resolution of the collision would be a consequence of multiple reads of the close proximity tags. This would also not be an issue with more sophisticated tag technology with collision avoidance (e.g. more sophisticated active tags)

Fig. 2. Emergency department layout (actual and as seen by the ABM)

For the RFID RLTS ABM simulation, the exact trajectories of patients are compared with estimated trajectories inferred from RFID tag reads. Patient trajectories through the ED are largely governed by the triage score, by HCW resources, as well as by issues such as social distancing as aspects of agent behaviour. Several primary cases are considered: under-provisioning, intermediate-level provisioning, and over-provisioning of readers throughout the ED. The primary metric used for determining the quality of the RFID placement is the spatial error in the patients' actual position as well as the temporal error (duration of time when the patient is outside of a reader's range). Economic cost considerations have not been included, although one assumes the cost and maintenance to increase monotonically with an increased number of readers.

Fig. 3 illustrates the model running with a placement of readers illustrated, highlighting a read of a patient tag as the patients traverses the ED. In Fig. 3, patients are moving between registration, triage, waiting and treatment rooms in a hospital ED. The reader placement is seen as a coarse grid of concentric dots and circles, with the radius indicating the reader range. The darkest colored circles indicate that a reader has just read a tag, whereas the lighter colored circles indicate that a tag was read some time previously. Simulation parameters are set to resemble actual records of wait times for EDs of similar resource (number of HCWs, ED physicians, capacity). Although not exact, patient arrival rates and service times are adjusted to reflect times (several hours) spend in ED waiting areas and treatment rooms.

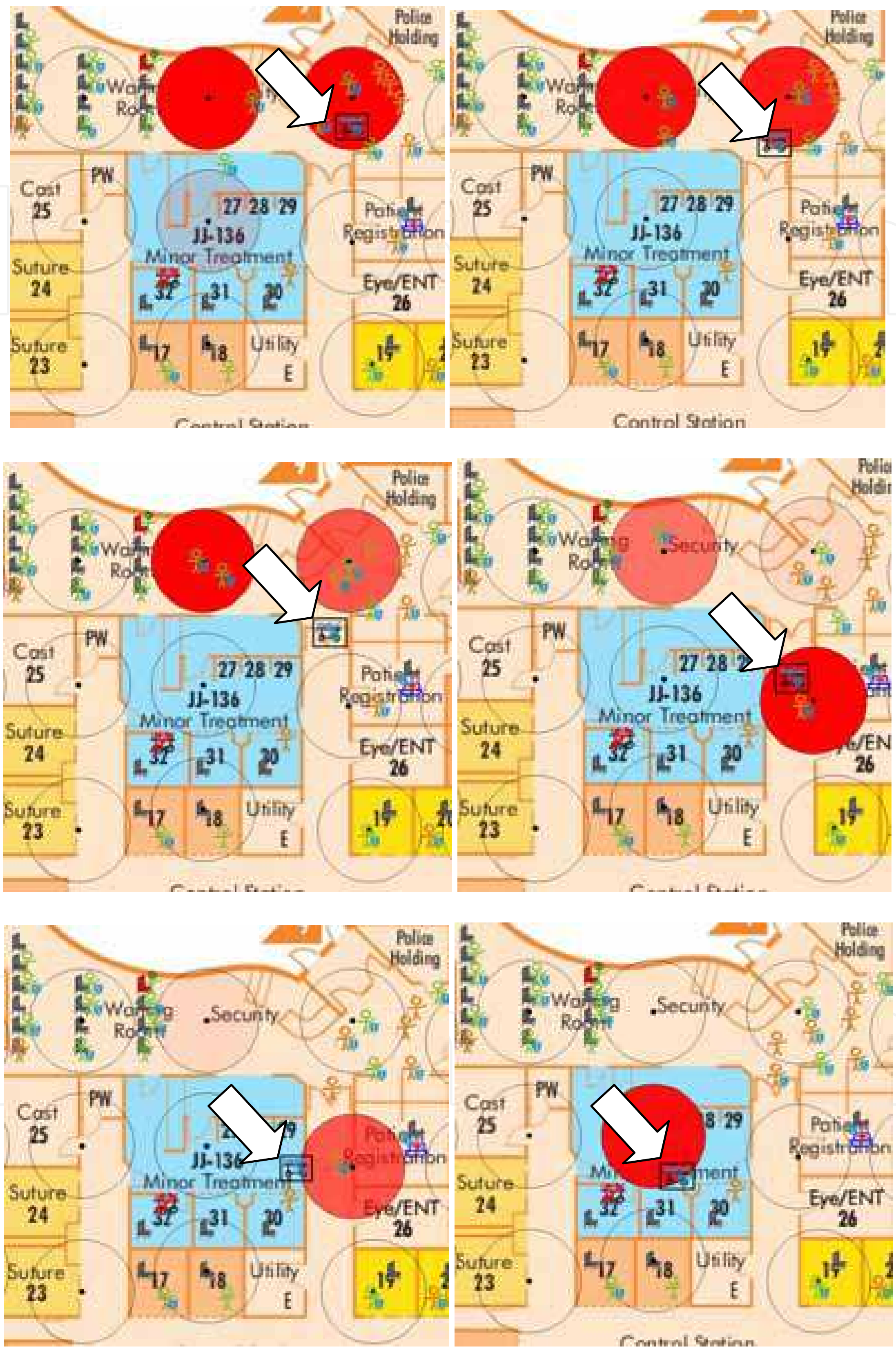

Fig. 3. Consecutive snapshots of patient trajectory (from entrance to treatment room)

3.3 Implementation details

The case study considered a modeling instantiation coded in an Object Oriented Language, C++ using Qt4 libraries running under the Linux operating system. For those interested in saving development costs, commercially available ABM frameworks/ toolkits such as SWARM (SWARM, n.d.), Repast (Repast, n.d.), and Anylogic (XJ, n.d.) come with varying out-of-the-box functionalities. This object oriented ABM approach has natural extensions to the sort of spatial modeling called for by the spatial nature of the system under study. It also should be noted that developing an ABM within a object oriented framework from the ground up provides an additional degree of understanding the problem in contrast to using a more commercial platform.

The simulated world is a two-dimensional (X, Y) discrete Cartesian world of extremely high resolution (floating point). An implicit assumption is that RFID tags are always at the reader level, which allows for the elimination of the Z direction. This type of design is also closely related to how a floorplan would be drafted with RFID readers overlaid, making implementation of such aspects more natural. The model is not general purpose, but is a spatially directed ABM aimed at institution-level simulation of a healthcare environment. While a custom ABM generates results that are unlikely to be reproducible because of subtle design differences between the implementations of various researchers, any sufficiently complex system is unlikely to be reproducible in practice. An application-specific ABM is not filled with rarely used or obscure features and design choices to support those features of a more general framework.

Within the object oriented approach, all agents and other entities in the system are implemented as objects with a geographical hierarchical decomposition (world locations in world). For partitioning the world further, there is a world grid in locations; however, the underlying space is still “continuous” (floating point specification of X and Y coordinates). The simulation loop calls a tick() method, the semantics of which are that the object (agent) is getting their slice of simulation time where they can react to other agents around them. Agents can access a limited number of features of other agents and objects, which can be set by the programmer, depending on the model. They can also pass messages to other agents in order to achieve interaction. For example, they can sleep until bumped or acted upon. Another difference between this and other modeling approaches is the lack of a scheduler which drives the simulation. Agents spend a high proportion of their time reacting to one another, that the scheduler would effectively be running each agent at every time step. For example, a patient can assess the number of patients waiting before them, and decide whether or not to leave the ED without treatment, based on their condition and a model of how long they will have to wait. We acknowledge that a scheduler or script may be of benefit to the efficiency of our custom ABM, especially when extending the model to simulate more complex time-of-day variation of patient arrivals and staffing schedules. Partitioning the space of the world, has the tendency to reduce the number of agents that each agent has to interact with at each time step, speeding the simulation.

Fig. 4 illustrates an object inheritance model that closely resembles the model used in this study. The RFID RTLS model builds upon an ABM that was initially developed for studying patient access (wait times) and was subsequently extended for application in modeling the spread of nosocomial or hospital acquired infections. The bold text illustrate the modifications to extending the ABM to modeling the performance of RFID RTLS in an ED. In addition to the RFID reader class, extensions were also made to support the data collection in terms of the error model.

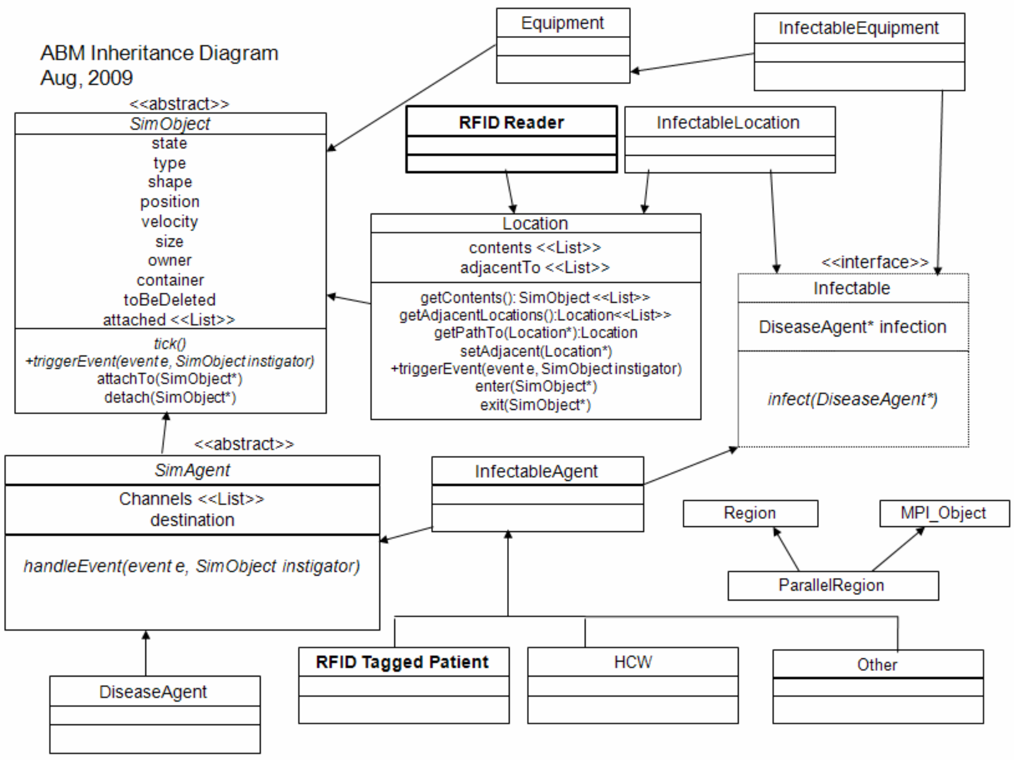

Fig. 4. ABM inheritance diagram with RFID extensions

Each agent acts in a set, predictable, but arbitrary order. That is, agents and all other objects are simulated in the order in which they were added to the simulation governed by the arrival rates of patients of various triage scores. Time is discrete with each time step having a resolution of 1 second (1 time step or tick = 1 second). Patients are modeled as occupying a circular space with a radius of 60 cm, representative of their physical person as well as a concept of personal space.

Using this technology, we model a hospital ED as a collection of interacting agents. Patients arrive and require treatment, and are tagged with an RFID tag upon entering the ED. Nurses and other agents that decide upon treatment paths for patients, for example an erController, direct patients through the system. Doctor agents treat patients. RFID readers are implemented in a similar way to agents, as a class extending the location class which read the tags of every patient that enters their reading radius.

Agents practice rudimentary path planning, typically choosing the shortest path to the destination location (e.g. travel from waiting room to treatment room). The agents also selectively practice microsocial distancing, where they will tend to distance themselves according to their local density. These are examples of localized agent decision making.

A simulated RFID reader notes when an agent (patient) enters its reading range, a roughly circular region with occlusions primarily due to walls. The RFID model requires a line of sight between the reader and tag; walls provide 100% attenuation in the simulation. The model can be modified to allow for propagation through walls, but would require an attenuation model to account for a reduced range in the previously occluded region. Furthermore we model regions of interference where multiple readers' ranges overlap. We employ a placement algorithm which attempts to place readers approximately equally spaced in a grid throughout the modeled ED floorplan. (The ABM also allows for readers to be placed manually as would be the case in an actual ED and more detailed planning). A heuristic places the reader on either side of a wall if the equally spaced grid placement algorithm should place the reader inside a wall. We call this a naïve grid placement strategy. Longer term goals of an ABM would be to further develop the feedback loop of an optimizer adjusting reader locations in a manner to minimize uncertainty. In doing so, one would also have to model the actual RF environment via a site survey, and model the performance of the RF system taking into account interactions in a system with a plurality of patients, visitors, HCWs, as well as portable equipment.

We do not receive a signal or notification when the tag leaves a reader's reading radius. Furthermore, we cannot expect better resolution from this system than the error resulting from the reader's own radius. That is, we know that a patient entered the radius of a circular reader area, and that the patient is known or thought to be in that particular reader's range until another reader event trigger. Therefore, we define error as 0 if read by a reader and the tag is within that reader's radius (line-of-sight does not need to be maintained). In general, with a tag within a reader's range, the tag may be read many times. These multiple reads in effect confirm the patient's proximity and are implicitly accounted for here. This is an optimistic error model as when an agent is within a read radius, the contribution to spatial as well as temporal error is zero.

Since ABM is very compute intensive, parallelism should be used wherever possible. Parallelism was implemented during the collection of data, as the ABM is tailor-made to not only exploit fine grained parallelism, but also exploitable at the coarse grain level (process). The latter parallelism was exploited here where individual ABMs would be run on a small compute cluster.

4. RFID patient tracking ABM simulation results

4.1 Variable reader configurations

The simulation parameters are summarized as follows:

- The emergency department layout is drawn on a 1464 by 2001 pixel grid, corresponding to an area of approximately 30m by 40m. While the scaling is not precise, it is chosen to be a reasonable representation.
- The RFID reader range was chosen as a circular region of 100 pixel radius (approximately 2m), roughly corresponding to the approximate reading radius of many newer passive readers.
- RFID reader spacing was varied from 100 pixels to 350 pixels between readers, in increments of 50 pixels. This created six reader configurations, hereafter noted as 100, 150, 200, 250, 300, and 350, respectively, and shown in Fig. 5. Readers are again indicated by black dots, with their ranges indicated by circles. Readers in the process of a read are highlighted. The placement scenarios are not optimal but are an attempt to capture patient flows through major traffic routes in the ED modeled.
- At each of the six reader configurations, the simulation was run 500 times, with roughly 200 patients visiting the ED in each simulation.
- The variable of interest in the simulations was uncertainty or error, defined as both spatial error and temporal error. The measure of spatial error used in this model is the difference in trajectory inferred from the readers, relative to a patient's actual position as known within the simulation. As such, when a person is recorded within the range of a reader, the spatial error would be zero. As the patient moves beyond the range of the reader, the spatial error is the Euclidean distance from the reader to the actual patient

position. The temporal area in this model is defined as the percentage of time that a patient is not within the range of a reader.

Other measures of error, such as Manhattan distances would be equally reasonable and well within the modeling alternatives. Once a patient moves within the range of another reader, both the instantaneous spatial and temporal error would return to zero. A complication occurs when modeling interfering readers (an over-provisioned scenario). Here a dead zone is modeled, reflecting the overlap of two readers' ranges. The difference to the error measure is that the read may be delayed as an agent enters a reader range which was reduced by a dead zone, contributing a longer period of proximity uncertainty or error.

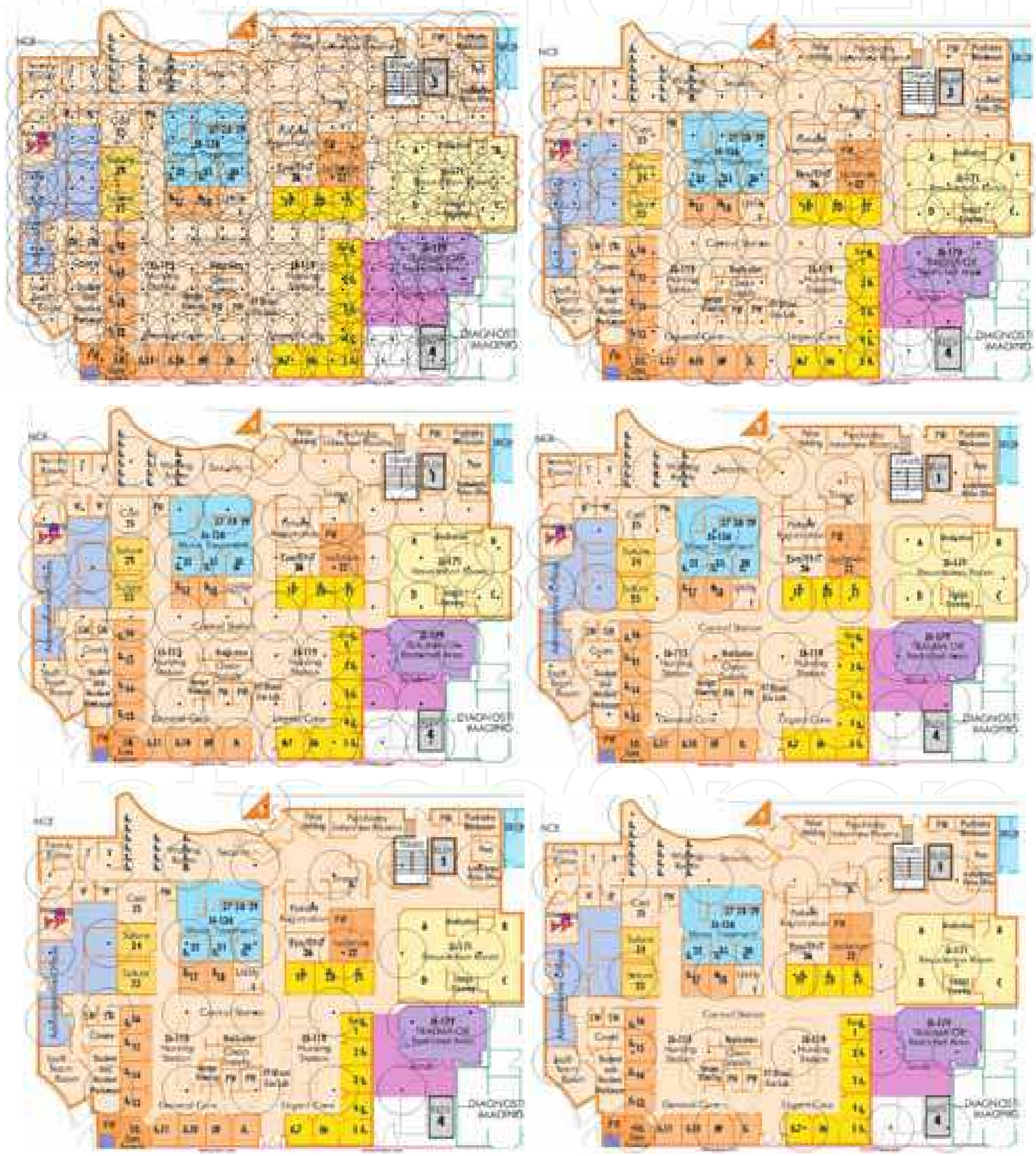

Fig. 5. RFID reader configurations (top left to bottom right: reader spacing at 100, 150, 200, 250, 300, 350 pixels).

Fig. 6 illustrates the typical spatial error between reader-inferred location and actual location for a single patient, plotted over the duration of stay in the ED, for the six reader configurations. The trajectory error illustrated is for a the reader arrangements seen in Fig. 5 and for typical patient instances. The behaviour of the patient is highly stochastic, governed by a number of random variables. In Fig. 6, the spatial error is plotted as being the Euclidean difference between the last read reader and the patient location once outside the read range. When a patient is within a reader's range the error is set to zero.

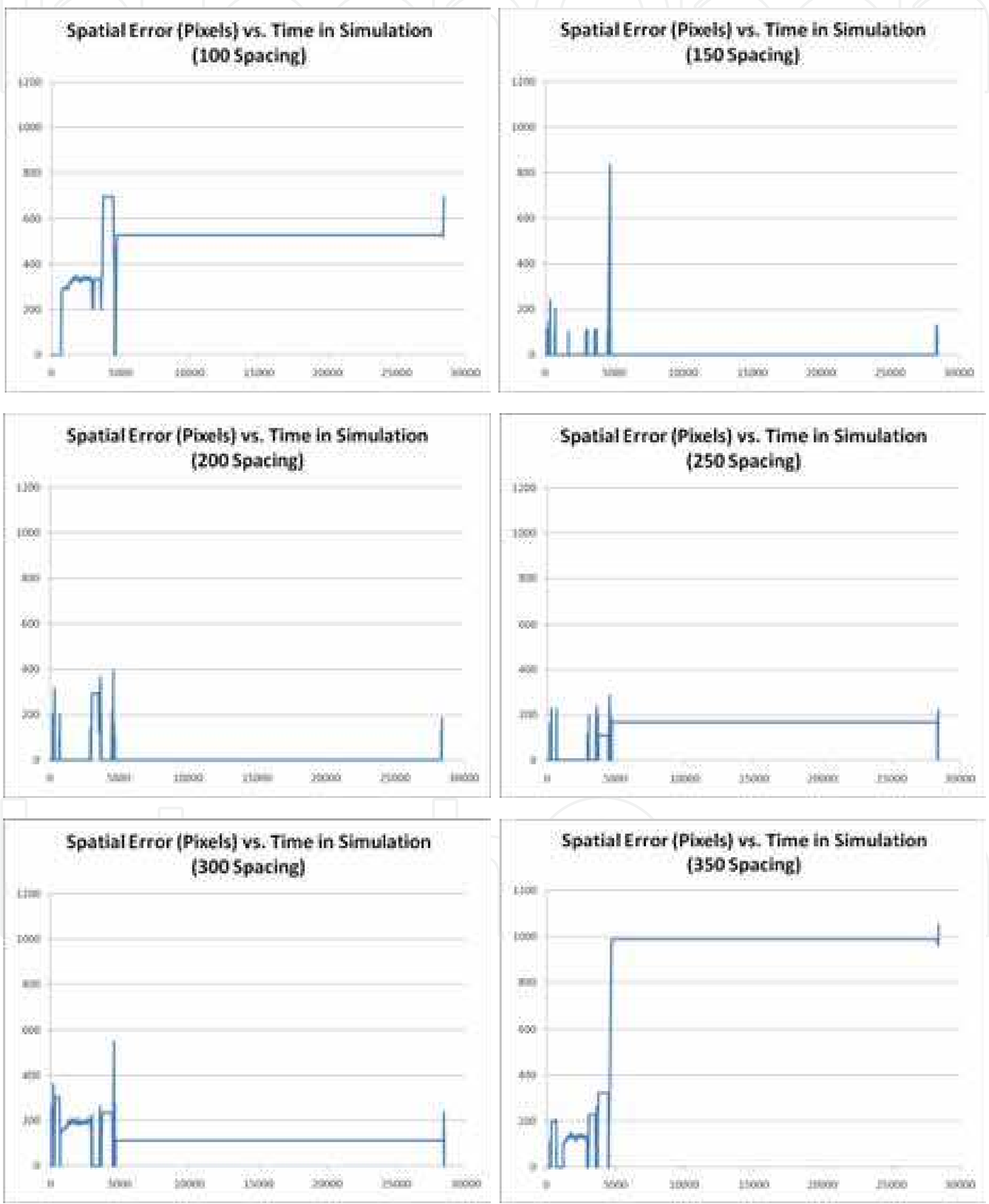

Fig. 6. Spatial error between RFID reading and actual patient location, for the same patient at each reader configuration

Fig. 7 and Table 1 summarize the normalized error for both spatial and temporal error. For example, in Table 1, (reader spacing of 350 pixels (sparse readers)), the patient would be in the read range of a reader 25% of the time, with a normalized error of 237 pixels or approximately 5 m. As the number of readers increase, the error or uncertainty is clearly reduced. The exception seen in Fig. 6 and Fig. 7 is the case of the reader configuration at 100 pixels, i.e. closely spaced readers with significant interference zones. Once a patient has been read by a reader, the patient is not considered to be in error if the patient moves out of the active read range and moves through or stays (waits) in an interference zone of that particular reader. However, if a patient moves into an interference zone of a reader and stays (waits) there, the patient is considered to be in error unless and until they move into the active read range of that reader and is read.

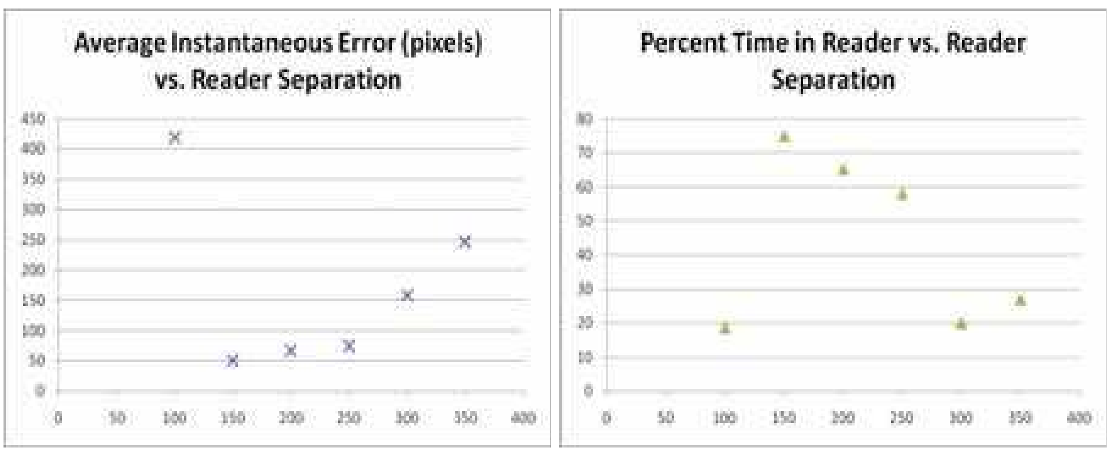

Fig. 7. RFID location errors (spatial and temporal)

Reader Separation	Probability of being in reader range	Variance of probability	Normalized Spatial Error (Pixels)	Variance of Spatial Error (St.Dev.)
100 (dense)	0.17 (17%)	0.08	407	38199 (195)
150	0.77	0.10	45	6212 (78)
200	0.64	0.11	71	6787 (82)
250	0.59	0.12	76	6225 (78)
300	0.23	0.08	156	6938 (83)
350 (sparse)	0.25	0.09	237	31099 (176)

Table 1. Summary of RFID location performance (spatial and temporal with variance)

One of the most interesting aspects of the simulation is the percentage of time that a patient would be in range of a reader. From these simulations, in an under-provisioned system, the patient's position may only be known approximately 25% of the time, whereas for the over provisioned case the patient's position is also known approximately 20% of the time. This highlights again the importance of strategic installation locations for the readers, to capture the major traffic flow patterns through the topography, taking into account that one can live with a high degree of uncertainty in certain areas with less in others. Depending on the RFID model, there likely is a near optimal configuration of readers that will minimize the uncertainty associated with an RFID RTLS.

It should be noted that although the uncertainty is generally decreased with an increasing number of readers, there is a point of diminishing return. Although not linear, the cost of provisioning and maintaining the ED with readers at 150-pixel separations is significantly greater than an ED with the readers at 250-pixel separations. In addition, we did not consider any inference of behaviour as a consequence of the location of the tag being read. For example, if the last read reader was located in the waiting room, one can likely infer that the patient is still in the waiting area until another reader reads the patient's tag.

4.2 Variable reader ranges

The case study further examined the performance of the readers in terms of their read radius. Readers and associated technologies tend to improve the range of RFID systems over time, whether passive or active. In this simulation, the readers' read areas are either decreased of increased by a factor of two from the baseline configurations outlined earlier.
The best case scenario from the previous placement of readers is denoted as 250, i.e. the readers being roughly spaced 250 pixels or approximately 5 meters apart. This best case scenario is argued as function of reader error and diminishing return if more readers are deployed (Fig. 7). Based on other metrics (Fig. 6), one could also argue that the reader configuration at 200-spacing is a best case scenario. As is typical, implementation-specific priorities and their associated metrics (cost, performance, etc.) define a best-case scenario for a given user. This section illustrates other variations of reader capability that are also easily modeled within the ABM framework. Fig. 8 illustrates the case where the reader range

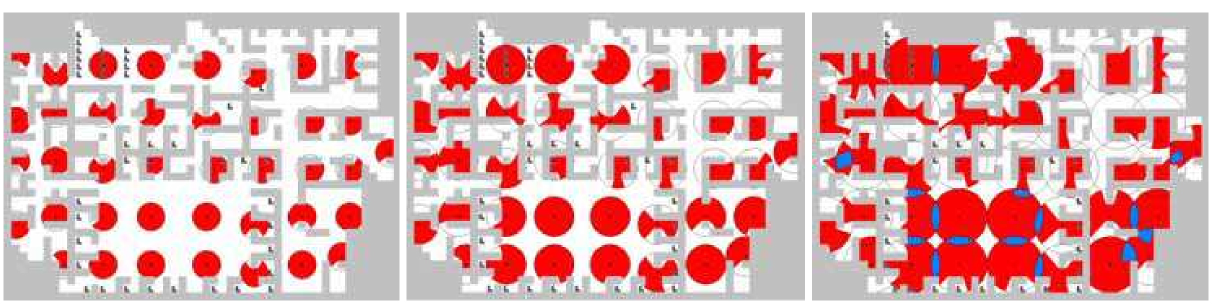

Fig. 8. RFID coverage (red) and interference (blue) areas for small, medium, large coverage areas.

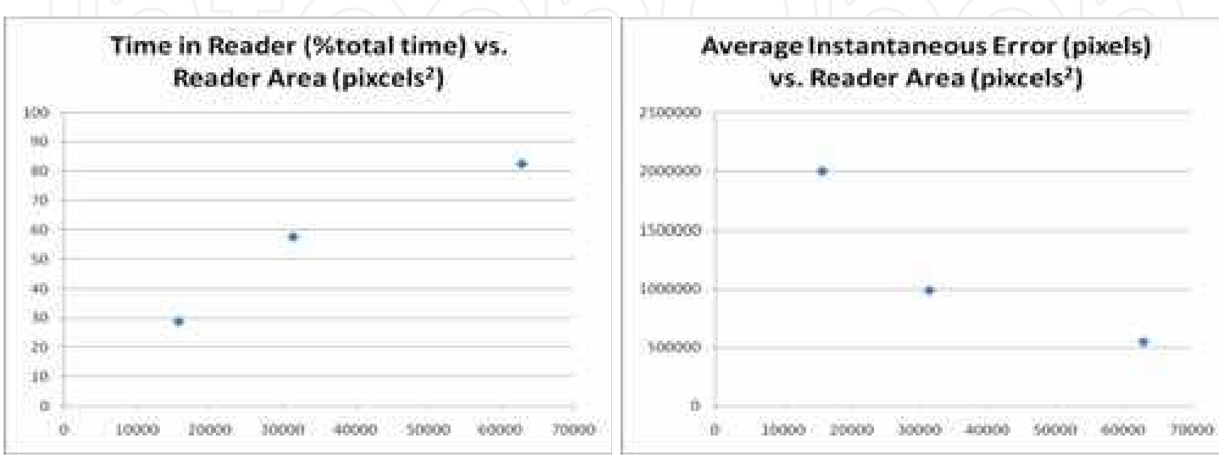

Fig. 9. RFID range performance (spatial and temporal)

(coverage area) is reduced or increased by a factor of ½ or two respectively. The middle illustration of Fig. 8 is the same as the previous case with readers spaced 250 pixels apart having a read radius of 100 pixels. An identical number of simulations were performed with the results presented in Fig. 9. Here one can see that the case of readers spaced at 250 pixels, with a 100 cm (1m) read range is likely reasonably close to the "near optimal" configuration. The trade-off again would be diminishing return if one were required to invest in the large coverage readers, as cost tends to increase with read range.

4.3 Error interpretation

It is difficult to illustrate explicitly the effect of the various errors seen with an arrangement of readers. It is however enlightening to attempt to graphically illustrate why some reader placements result is large error in estimating the patient's location. Fig. 10 illustrates the coverage areas, blind spots, and regions of modeled interference. Red illustrates coverage area, with blue representing regions of interference (the over provisioned case). Ideally the reader would have a circular red read area. Degraded read regions would be a result of walls and obstructions where the tags would not have a clear path to the reader and thus, in the passive case, be unable to acquire sufficient energy to function. Degraded performance also occurs in regions of reader interference where the readers are too closely placed. From this perspective, it is relatively easy to identify poorly performing patient trajectories. For example, from this illustration and observation of patient trajectories, one can envision a patient making their way to a treatment room not equipped with a reader and waiting there for treatment for a considerable period of time. In these cases (which may be pathological) the error can be considerable over hours of wait time. In Fig. 10 the arrows illustrate a path a patient may traverse to a treatment room (left). Overlaying the view seen by the ABM (right), one can see that the patient trajectory traverses a region of considerable interference (horizontal arrow), and ending at a treatment room without read coverage (occluded due to walls).

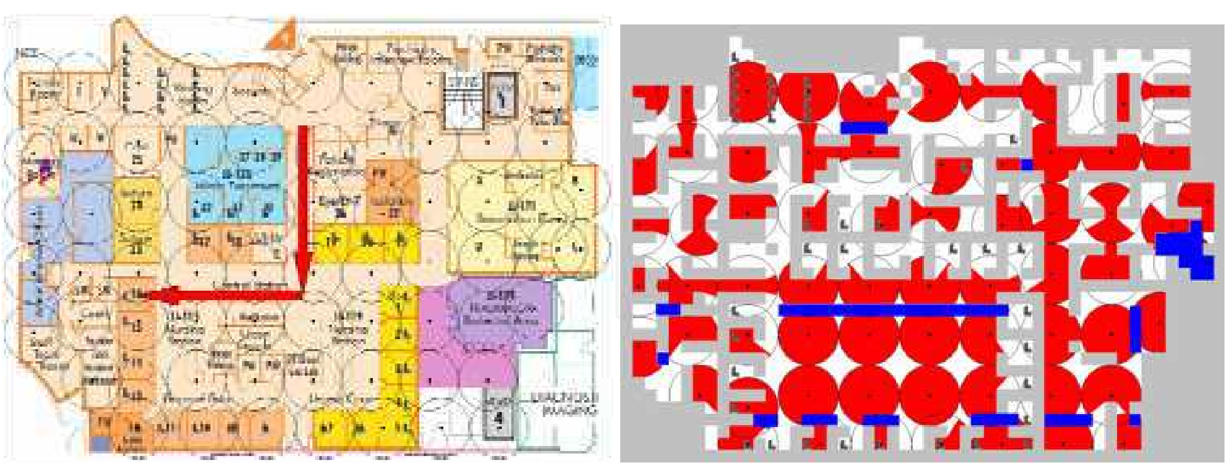

Fig 10. Trajectory of outlier patient with high temporal and spatial error (left), reader coverage (right), interference regions in blue, readable areas in red

Fig. 11 illustrates the difficulty with simply increasing reader density if interference is a problem. Red illustrates the percentage of floor space covered by readers while blue illustrates regions of interference. This corresponds to the high error seen in Figures 6 and 7 in the case of reader spacing at 100 pixels (over-provisioned), where interference is modelled as error.

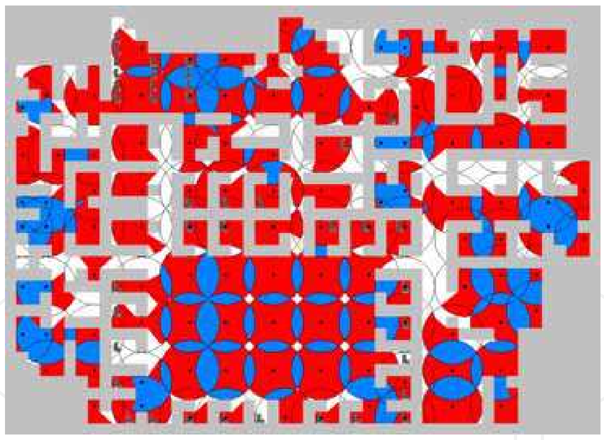

Fig. 11. Dense reader spacing leading to increased interference regions.

There are techniques (beyond the scope of this chapter) for reducing the error associated with estimation of patient trajectories. The simplest are those based on the Kalman algorithm as well as others based on conditional probabilities (Bhatia et al., 2007). Fig. 12 illustrates a histogram of a passive tag's maximum read distance from a GAO GP-90 passive reader using clamshell tags. The data was collected under ideal conditions and as such represents a bound to error anticipated in the read itself. It does however lend credibility to the ABM with fairly abrupt read ranges simulated. Any backend system deployed for collection of RFID RTLS data would presumably be also equipped with estimation software to further reduce error.

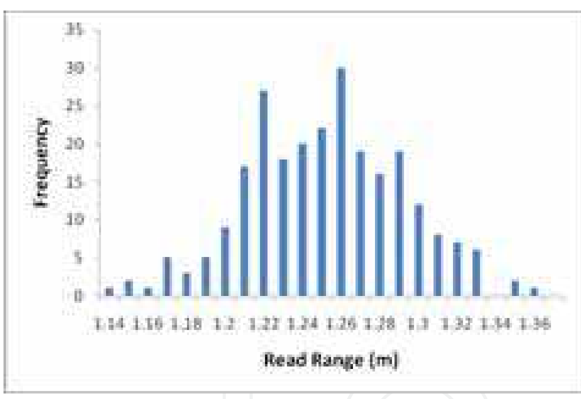

Fig. 12. Histogram of GP90 read range.

5. A simple prototyped RFID RTLS

The RFID RTLS application modeled using an ABM approach may be a conventional RFID application in healthcare, yet its implementation demands strategic consideration of hardware and software details and integration. This chapter closes with a brief discussion of a desirable architecture, emerging best practices, and available technologies to create an RFID RTLS using Supervisory Control and Data Acquisition (SCADA) loosely based on Service Oriented Architecture (SOA). The prototyped framework represents an integration of technology, architecture, software and RFID devices that leverages existing software systems, with an emphasis on being IP-centric and application- and device-agnostic.

The basic notions are derived from the requirements of a framework incorporating the best practices from existing data acquisition systems as well as underlying communication systems. The current generation of RFID RTLS are purpose-built hierarchical network architectures and tend not to leverage more modern advances in SOA. SOA is meant to overcome the difficulties of creating distributed applications by making the data and programmatic communications between entities over a distributed network transparent to the developer. The overall architecture of an RFID RTLS is illustrated in Fig. 13.

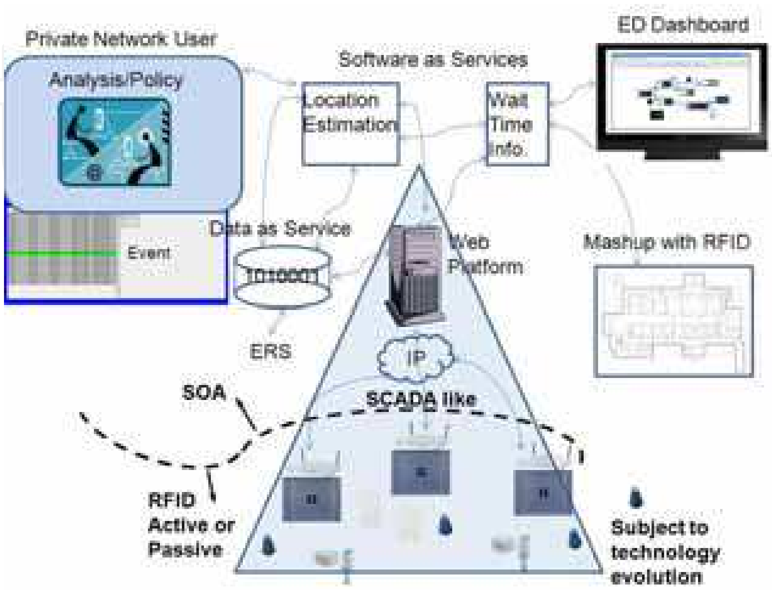

Fig. 13. Overall SOA SCADA RFID RLTS architecture

5.1 RFID RTLS system components

The prototyped RFID RTLS installation uses the principles of a SCADA system. The primary objective of SCADA is to remotely monitor and/or control remote devices over a communication channel and present the data back to the user in a friendly manner. Another possible feature of SCADA is the capability to not only acquire data but also to record it for future analysis. Furthermore, SCADA systems can log information about the status of the remote equipment. As such, SCADA is well suited as a part of a data collection platform for an RFID RTLS. A minimal SCADA system is composed by at least one Master Station (MS) computer, at least one communication channel to the Remote Transmit Units (RTU), and the Remote Transmit Units connected to a sensor or device that collects data.

Typical industrial applications of SCADA include system control of electrical networks, gas pipelines or weather stations across a region or country. The prototyped application incorporated SCADA technology with an improved architecture, thereby leveraging much of the legacy of the data acquisition and industrial proven stability of SCADA systems. While SCADA systems are well suited to data collection, their evolution to networked applications has been slow. SCADA applications lag well behind many internet applications which typically do not require any type of interface to data collection systems but more typically are terminated at a terminal or computer with a human user interface. It is the integration of SCADA and SOA that is compelling as an architecture for an RFID RTLS.

The prototyped application collects the location of the traceable individuals (patients) and equipment in a personal care home setting, with each element equipped with an RFID tag. The system stores the information relative to the time and location of the last identification of a particular element. The definition or granularity of the system depends on the number

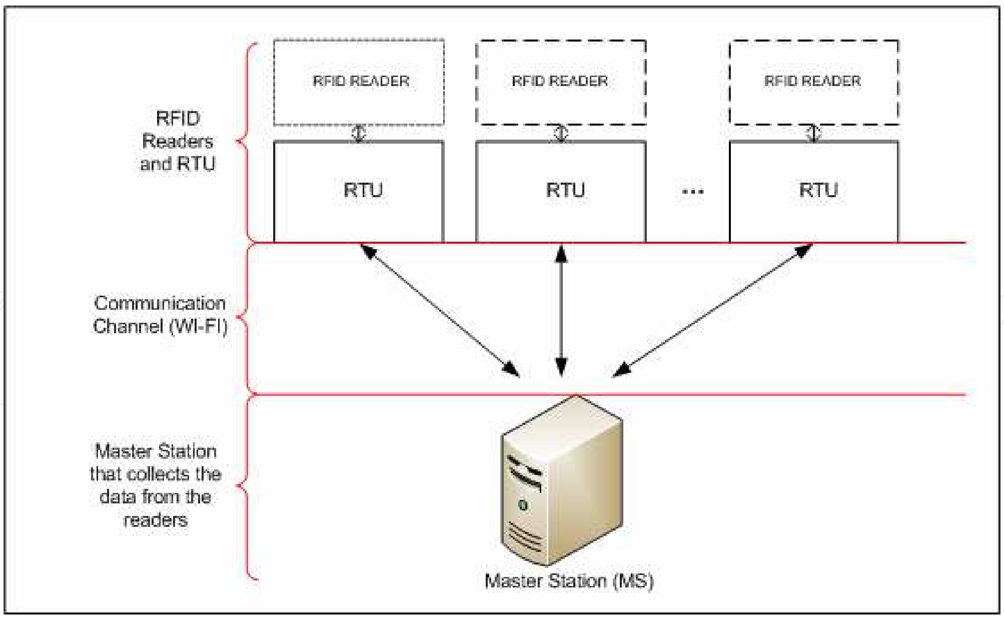

Fig. 14. A Minimal SCADA system (IEEE, 1994).

of RFID readers installed, each equipped to send the data to the MS. Each reader is equipped with an RTU that interfaces the serial communication port from the RFID reader to the existing wi-fi in the building. Finally, data is collected by a computer and presented to the user using a simple web interface or GUI application.

Ideally RFID readers should be installed in different locations within a building in a somewhat optimal configuration, guided by planning tools such as the ABM discussed in previous sections. The system should have as many sensors as the level of accuracy and precision desired in the positioning and tracking within a building. When an element with a tag is in the read range of a reader, the reader will detect the tag ID and it will transmit it to the MS. The readers used here were the GAO GP90 readers for passive tags. The tags used were the long range (1-2 m) passive clamshell type.

The communication module is responsible for sending and receiving the data to/ from the readers and the MS. The options to establish a communication channel between the readers and the MS are multiple. The one selected for this implementation is wi-fi (802.11). The reasons for the decision are: the wi-fi infrastructure exists already in the building where the RTLS will be installed; cost savings in the installation because there is no need to install single cables per reader; considerable bandwidth to transmit tag IDs; and, open standard with low or no interference (well developed medium access control protocols).

Each reader has a RTU built with two ports: a serial port to communicate with the RFID reader and a built-in wi-fi connection to communicate to the remote system. The module used is the RCM5400W from Rabbit Semiconductors. This module has a Rabbit 5000 series microprocessor. The software can be easily written in Dynamic C, based on ANSI C. The small size of the board make is simple to mount in a small enclosure or even within the RFID reader.

In the development of the prototype, the MS was assigned a pre-defined and fixed IP address. Each RTU was assigned a unique non routable IP address from the MS which served as a DHCP server. Ideally as part of a networked environment, the MS would also be assigned a dynamic IP address. The RTU serves as an interface between the RFID reader and the wi-fi communication channel. The RTU has two functions: 1) send the data to the

MS addressing the packages to the MS IP, and 2) the MS can PING each RTU to know if it is live or not. The other elements of the wi-fi network are the access points necessary to carry the signal to each RTU and the wi-fi board in the MS. The overriding principle is that even as the physical layer RFID technology changes, much of the backend can remain the same.

The SCADA software is an innovative approach based on years of in-field use and research. The SCADA software typically has three modules. The modules can run on the same or different systems based on the load and resources available. The first module is the communication module. This module handles the communications between the MS and the RTUs. Each time a RTU has data to send, the communication module is responsible for receiving and storing it in a database. Also, this module checks that the wi-fi network is working and that each RTU is live every preset number of seconds. The second module is the database module. This module receives the data from the communication module and stores it in a database. It also stores configuration information for the system to run. The third module is the presentation module. This is the module allows the user to see the location of each tag associated with an individual or equipment, in a user-friendly manner. There are two possible alternatives: 1) a web based application; or 2) an application that can be installed. Each module has a specific task, and the interaction between them facilitates the system functionality.

To interact with one another, each module is implemented as a SOA. There are multiple definitions for SOA, but the OASIS group (2006) defines SOA as a paradigm for organizing and utilizing distributed capabilities that may be under the control of different ownership domains. It provides a uniform means to offer, discover, interact with and use capabilities to produce desired effects consistent with measurable preconditions and expectations.

Each module has functions that can be called or invoked by remote modules. For example, the presentation layer can ask the communication module for a location for a particular individual or equipment. Because the communication module remembers the last reading, it will provide the information without need to query a database. In the same way, each time a reading arrives at the communication modules, it stores the information into a database, calling a database storage procedure located in the database SOA module. Each module is independent of one another and each can be local or remote. However, reliable communication links are necessary for proper functionality.

In general, the prototyped application is built on a modularized approach, with each module governed by modern SOA principles. To a large degree, the modules are independent of one another, allowing for demonstrable rapid prototyping, an emphasis on reuse, and the utilization of existing infrastructure. Although this application does not explicitly utilize a formal SOA, it illustrates many of the benefits. Specifically, it is – to a large degree – access technology agnostic: wi-fi or cellular can be replaced without interfering with the functionality of other modules. It is also largely RFID technology agnostic: the technology or vendor can be interchanged with little code modification. For example, the transition from a passive to an active tag can be relatively easily accommodated. The SOA layer at the application level gives each module independence and flexibility. Moreover, it allows the presentation layer to access information about the readers through data services. As algorithms are developed for improved estimation, for example, the location estimation module would be replaced or modified without further disruption. Additional data must also be supported in a flexible manner. For example, if parameters associated with signal reception strength were to be used as input to an estimation module this should only be a change in the XML that is used to support the data encapsulation. An additional benefit of an SOA for an RFID RTLS within a healthcare facility is that these systems are required to integrate or dovetail with other healthcare systems at some level, be it other RFID applications or the existing hospital electronics records system. Although not described in detail here, it should be noted that as a consequence of being heavily IP-centric, all of the existing security advancements of the IP community can be readily deployed here.

6. Conclusion

RFID based RTLS systems hold great potential to play a significant role in augmenting electronic records systems in healthcare. However, they are not without their limitations. One of the more challenging obstacles to overcome is dealing with the inherent uncertainty of relatively low cost RFID systems, as illuminated by the modeling and simulations in this case study. As such, the agent-based modeling techniques are particularly well suited to modeling RFID-enhanced healthcare systems. In mitigating uncertainty, some backend processing is required. As RFID systems continue evolve and more sophisticated tags are deployed, it is reasonable to expect additional levels of physical layer triangulation to be employed, as well as more intelligent protocols that may also query tags in an attempt to yet further reduce location estimation error. Many of these issues will be resolved in evolving medium access control protocols as well as at the application layer for the RFID RTLS system. Nonetheless, this chapter illustrates the role that ABM has in provisioning a RFID based tracking system, and further modeling extensions to refine the characteristics of the topography and agents will enhance the results.

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Radio frequency identification (RFID) is a fascinating, fast developing and multidisciplinary domain with emerging technologies and applications. It is characterized by a variety of research topics, analytical methods, models, protocols, design principles and processing software. With a relatively large range of applications, RFID enjoys extensive investor confidence and is poised for growth. A number of RFID applications proposed or already used in technical and scientific fields are described in this book. Sustainable Radio Frequency Identification Solutions comprises 19 chapters written by RFID experts from all over the world. In investigating RFID solutions experts reveal some of the real-life issues and challenges in implementing RFID.

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