Improvement of RFID Tracking Accuracy for a Personnel Tracking System in Healthcare

By

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Abstract

Radio Frequency Identification (RFID) technology has been widely adopted by different industries for various purposes. While implementing a RFID system for personnel tracking in an industrial environment, such as a hospital, the tracking accuracy is not always satisfactory due to incorrect placement of RFID hardware, coarse system configuration or environment. This thesis proposes comprehensive optimization methods for improving the tracking accuracy of a RFID system for personnel tracking. The improvement is achieved from four perspectives including RFID data cleaning, experimental design, data fusion and simulation modeling. This research is based on a case study carried out in a local community hospital where a RFID system for personnel tracking has been implemented. Through applying the optimization methods, the tracking accuracy of the RFID system has been improved to 87.33%. The thesis provides a guideline for the hospital and other similar application environment to implement improvement methods on a RFID tracking system.

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Dedication

To my family and my fiancée

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List of Abbreviations

Abbreviations	**Full Names**
ABM	Agent-based Modeling
ANOVA	Analysis of Variance
dBmW	Decibel-milliwatts
DOE	Design of Experiments
ED	Emergency Department
MHz	Megahertz
MTA	Minor Treatment Area
RSSI	Radio Signal Strength Indication
RFID	Radio Frequency Identification
UHF	Ultra High Frequency
WRHA	Winnipeg Regional Health Authority

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Chapter 1

Introduction

1.1 Background

Radio frequency identification (RFID) is a technology for automatic wireless data collection and identification. For its simplicity in use and decreasing hardware cost, RFID has been widely adopted in various areas, including healthcare, manufacturing, retailing, transportation and so on. RFID market in healthcare is expected to achieve a compound annual growth rate of 29% over the period of 2010 – 2014 (TechNavio, 2011). With the help of RFID technologies, healthcare institutions are able to realize functions of patient tracking, medical assets localization, security management, drug management and many other functions. With a desire to enhance healthcare service efficiency and facilitate personnel management, a RFID system for personnel tracking has been adopted by the Emergency Department (ED) in Seven Oaks General Hospital (SOGH), the busiest community hospital in Winnipeg, Canada. The system is in its pilot test stage and currently experiencing difficulties that are caused by duplicate and unreliable readings. A common scenario of the problem is that a tagged person is detected by multiple readers at the same time, which causes the confusion of the person's exact location. Under this background, this thesis discusses the improvement of tracking accuracy for a RFID personnel tracking system conducted through the research cooperation with SOGH ED.

In the following sections, an overview of RFID technologies and applications will be presented first followed by research objectives and the thesis outline.

1.1.1 RFID Technology Overview

RFID is a technology that utilizes radio frequency signals for wireless communication and automatic identification between RFID readers and tags, the two major components of a RFID system. Other components of a RFID system include RFID middleware, computing hardware and application software.

An RFID tag can have diverse design appearances but basically consists of an integrated circuit and a microprocessor chip with memory. An RFID reader and a tag communicate in two ways, either through electromagnetic induction or electromagnetic radiation. A passive tag does not use a battery as power supply with usually low frequency, it communicates the reader through the electromagnetic induction, while an active tag which uses a battery to power itself with usually high frequency communicates the reader through the electromagnetic radiation. Also, for a successful communication, the reader and the tag must be in the same frequency and use the same protocol. Because of the communication methods, a low frequency RFID system is usually used for short range applications and a high frequency system is used for long range applications. A tag can be read by a reader from several centimeters to hundreds of meters without being in the line of sight with a reader. This means a reader does not necessarily need to see the tag before it can read the tag, and this is an advantage of RFID technology over the bar code technology.

Each RFID tag stores an ID number in its chip. If a reader interrogates a tag successfully, the tag will response with its ID included. The tag's size ranges from the size of a grain of rice to the size of a bank card, which is easy to be carried. If a tag is attached to an object or a person, the object or the person can be identified at the proximity of the reader that detects the tag.

The structure of a typical tag reading record is shown in Table 1.1. Each tag ID contains 9 bytes. The first 8 bytes in the structure represent the ID of the tag. The battery and tag type information are represented by the last byte whose structure is shown in Table 1.2. If the battery is sufficient, a "1" will be shown, otherwise, a "0" represents the insufficient battery.

Table 1.1 Tag Reading Record Structure

0	1	2	3	4	5	6	7	8
Tag_ID								Status

Table 1.2 Structure of Last Byte in a Tag Reading Record

7	6	5	4	3	2	1	0
Battery				Tag_Type			

With the above structure of tag reading record, the reading data is transmitted from a tag to a reader in a data package whose example structure is shown in Table 1.3. The Header of the package contains 10 fixed bytes for all types of data packages between the reader and the PC, and can be used to validate the data packages. An example of the decimal values of these bytes are shown in Table 1.4 for validation purpose. The version field shows the protocol version number. Length field in the package indicates the length of the data package. Command indicates the type of the data package. Content field is used to store parameters for the command. Buffer stores the tag reading records. Every record is 13 bytes means a Buffer of size 1300 can store up to 100 reading records.

Table 1.3 Structure of Data Packages

Field Name	**Number of Bytes**	**Position**	**Value**
Header	10	0 ~ 9	Fixed
Version	2	10 ~ 11	Fixed
Length	2	12 ~ 13	48 + Buffer Size
Command	2	14 ~ 15	(Data[14] = 1) OR (Data[14] AND Data [15] = 0)
Content	32	16 ~ 47	0
Buffer	1300	48 ~ 1347	Tag Reading Records

Table 1.4 Decimal Values of Data Header

Byte	0	1	2	3	4	5	6	7	8	9
Value	66	73	83	65	95	82	70	73	68	0

1.1.2 RFID Application Overview

After being used by British fighters for the first time in World War II for detecting friends and enemies, RFID has been widely adopted in many fields nowadays, which includes medicine, aeronautics industry supply chain, construction, automotive and retail (Domdouzis et al., 2007).

As an example of RFID applications in medicine, RFID tags can be attached to blood bags or drug boxes. RFID readers can scan the tags wirelessly and find the right bag or box for a specific patient. With searching the tag ID in a pre-defined database, the blood bag or the drug box is easy to be located and identified. The RFID system not only accelerates the speed of locating a blood bag or a drug box but also reduce the probability of matching a wrong blood bag or a drug box with a patient.

For supply chain industry, no matter it is aeronautics industry supply chain such as Boeing, or retail supply chain represented by Wal-Mart, the RFID plays the similar important role. With RFID tags attached to crates that contain manufacturing equipment or food boxes, the content information about the loaded crates will be automatically obtained by the RFID readers installed at the gate of depot and matched with order information stored in the system in advance. The RFID technology facilitates the process of warehousing and increases the efficiency and accuracy of data recording by warehouse workers. Figure 1.1 demonstrates an application of RFID systems in a manufacturing system to track material flows and supply information (Smartag, 2014). This system is effective for the management of manufacturing and logistics system developed by Smartag. Wal-Mart, as the world's largest retailer, is a leader in applying RFID throughout its supply chain. It also required its suppliers to use RFID for tracking cases and pallets (Want, 2004). Another example is Mama's tomato sauce supply chain management system, where RFID tags are affixed to each can of tomato sauce for product tracking throughout the supply chain and even to the product end-of-life (e.g. recycling) stage (Want, 2004).

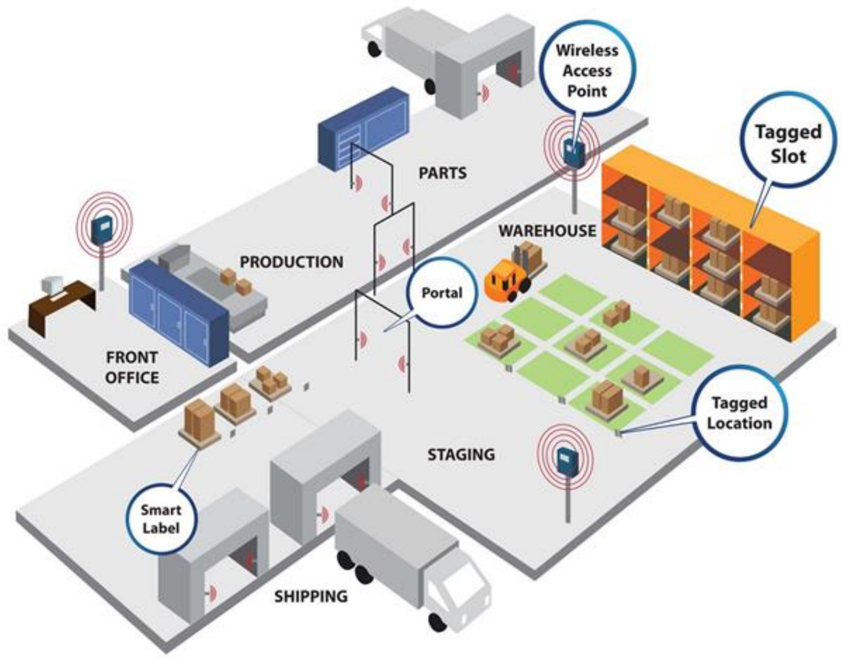


Figure 1.1 RFID System for Manufacturing and Logistics (Smartag, 2014)

Goodrum et al. (2006) did trials by tagging tools on two construction jobsites to help construction crews locate the tools when they are needed in order to improve the inventory management. Other typical application examples of RFID are aeronautics equipment tracking in shipment and assembly parts tracking in automotive industry (Domdouzis et al., 2007).

1.2 Problem Description

This section describes problems that currently exist in the RFID system in SOGH ED. To identify the problem, Figure 1.2 shows the layout of the Minor Treatment Area (MTA) in ED where the RFID system is implemented. The yellow squares in the figure represent readers and the green circle around each reader assumes the read range of that reader. In fact, the shape of the read range cannot be exactly same with the expectation based on the tests at the start of this research. As the system is implemented in such a hospital environment with rooms and hallways in a limited area, the read range of a reader is easily affected by many factors either from the system itself or from the environment.

The most obvious problem existing in the current RFID system is duplicate and unreliable readings. In fact, this is an inherent problem of many RFID systems (Jeffery et al., 2012).

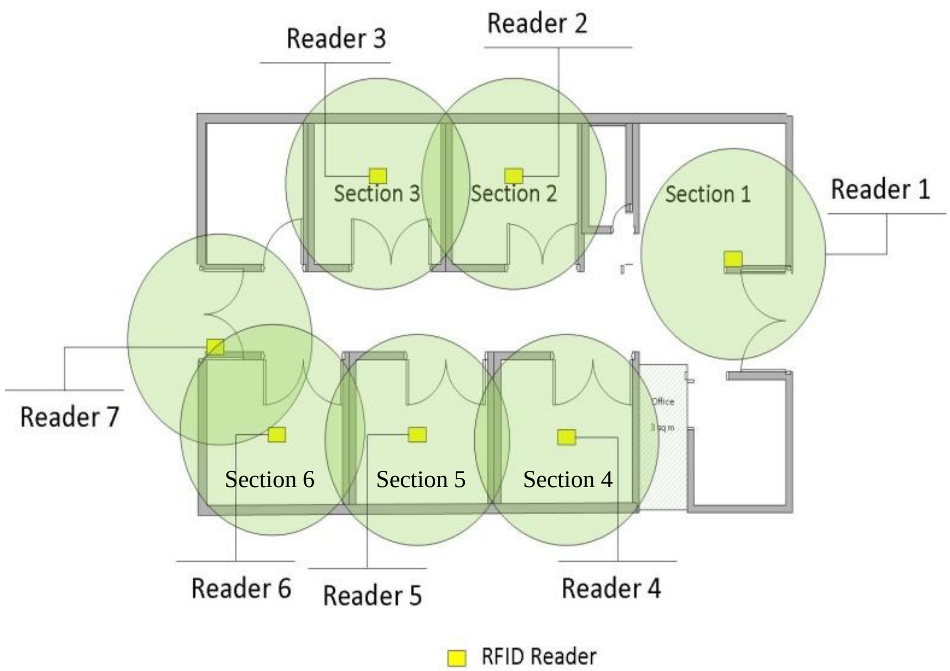
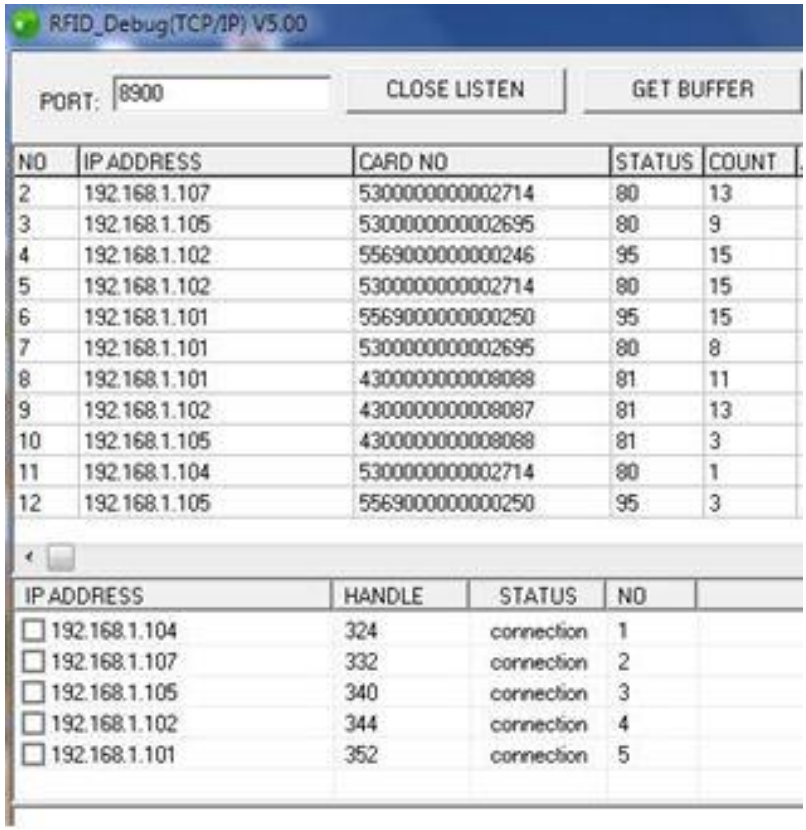


Figure 1.2 Layout of MTA, RFID Readers and Read Range

Duplicate readings are generated when a tag is consecutively detected by a reader. The duplicate readings generated within a very short period of time are meaningless to the application if there is no event occurred on the tagged person. Moreover, the huge amount of duplicate readings will overflow computer database. Hence, the duplicate readings have to be cleaned in order to keep a tidy RFID dataset.

False positive reading happens when a reader reads a tag that is actually not within its corresponding target area. This type of readings emerge in two situations: (1) When a tagged person is in the overlapping area of two or more readers, such as the big overlap between readers 6 and 7 shown in Figure 1.2. The tag in this case might be simultaneously read by two readers, of which only one is correct. This problem can be observed from RFID middleware shown in Figure 1.3 which shows a tag with tag ID ending with 2714 is read by readers with the IP addresses ending with 102, 104 and 107 respectively at the same time. (2) When a tagged person is moving in somewhere that is not designed to be covered by any reader such as the hallway in Figure 1.2 but the person reaches the edge of a reader's read range unintentionally. The reader will take the person as entering its target area and then the false reading emerges.

Although RFID has various advantages and applications, the noise readings can take too much resource, lead to tracking confusion and hinder ED staff from knowing the exact location of a tracked person. Hence, an effective approach for reducing these noise readings to improve the accuracy of RFID systems is needed.



NO	IP ADDRESS	CARD NO	STATUS	COUNT
2	192.168.1.107	5300000000002714	80	13
3	192.168.1.105	5300000000002695	80	9
4	192.168.1.102	5569000000000246	95	15
5	192.168.1.102	5300000000002714	80	15
6	192.168.1.101	5569000000000250	95	15
7	192.168.1.101	5300000000002695	80	8
8	192.168.1.101	4300000000008088	81	11
9	192.168.1.102	4300000000008087	81	13
10	192.168.1.105	4300000000008088	81	3
11	192.168.1.104	5300000000002714	80	1
12	192.168.1.105	5569000000000250	95	3

IP ADDRESS	HANDLE	STATUS	NO
192.168.1.104	324	connection	1
192.168.1.107	332	connection	2
192.168.1.105	340	connection	3
192.168.1.102	344	connection	4
192.168.1.101	352	connection	5

Figure 1.3 Sample Data Received from the RFID System

1.3 Research Objectives

The overall objective of this research is to improve the tracking accuracy for a RFID personnel tracking system. Three improvement methods of different perspectives break down the overall objective into three sub-objectives correspondingly. The first perspective is from data cleaning viewpoint. The aim of data cleaning is to obtain correct reading data by filtering duplicate and false readings. Secondly, as a RFID system that is not well configured may lead to some unreliable readings and limit the successful application of data cleaning algorithms, hence, a system optimization method is used to find the best setting for the system. Thus, the unreliable readings will be reduced and the data cleaning method will be able to perform best in an optimized environment. The third method to improve the tracking accuracy is from the perspective of data fusion. The objective of data fusion is to eliminate specific type of false positive reading by utilizing another assisted sensor data source. In addition, a simulation model is built with the aim of studying the RFID system and implementing more improvement methods in a cost-effective and time-efficient way.

1.4 Thesis Outline

This thesis mainly discusses the improvement of the tracking accuracy for a RFID personnel tracking system in healthcare. The thesis has eight chapters. Chapters 1 and 2 present the background, existing problems and related work. Next, the existing RFID system including the system hardware, software, application environment will be introduced in Chapter 3. Then, the proposed improvement methods from three perspectives will be discussed in Chapters 4 to 6 one after another. Chapter 7 will discuss the simulation modeling of the RFID system. The last part consists of research conclusion, recommendation and future works in Chapter 8.

Chapter 2

Literature Review

RFID has been adopted by different industries for various application purposes. No matter which application purpose it is, the tracking accuracy is always a critical index to measure the system performance. In this chapter, the general RFID application in healthcare and the methods for improving reading accuracy will be reviewed first in Section 3.1 to have a general overview of the current development in this field.

Secondly, as the unreliable reading is an inherent characteristic for RFID systems, various attempts have been done to solve this problem under different application areas. System-level methods to improve tracking accuracy will be reviewed first in Section 3.2. In order to understand the improvement methods from RFID data stream cleaning perspective, different unreliable reading elimination algorithms will be reviewed in Section 3.3. Also, in order to study the optimization method for a non-deterministic system with various variables and factors such as the RFID system, the current literatures on the topic of applying Design of Experiments (DOE) for RFID system optimization will be reviewed in Section 3.4.

Lastly, for future studying the RFID system from more aspects in a cost and time effective way, the simulation modeling methodology is a good approach to realize this. Therefore, the agent-based modeling (ABM) technique that provides a flexible model by building one from the viewpoint of the system's individual component fits our requirement very well. Some related works will be reviewed for gaining some ideas about how to build a simulation model for the RFID system in healthcare.

2.1 RFID Application in Healthcare

Following manufacturing and retail, healthcare is considered as the next home of RFID (Wang et al., 2006). Healthcare has also been listed as an emerging major application area of RFID by (Ngai et al., 2008, Liao et al., 2011, Li et al., 2006). Healthcare industry applied RFID mainly for the objectives of improving patient monitoring safety, increasing asset utilization, reducing medical errors and enhancing supply chain efficiency (Zhu et al., 2012).

For the sake of patient monitoring, Corchado et al. (2008) proposed an intelligent system that incorporates several technologies such as RFID, Wi-Fi and handheld devices. The system is for improving healthcare delivery in geriatric residence. The role of RFID in this system is for tracking and locating Alzheimer's patients over 65 years old. Several RFID readers were installed at different locations in the experimental area that is the first floor of a geriatric residence. The patients were attached with RFID wrist tags so that their locations could be tracked when they moved in the area. Besides Alzheimer's patients, RFID can also be used for tracking other vulnerable patients such as tuberculosis patients (Lai et al., 2010), children (Iadanza & Dori, 2009) and newborn (Ou Yang et al., 2009). Similar applications of using RFID for tracking are discussed in Fry and Lenert.'s paper (Fry & Lenert, 2005). In particular, RFID was used for tracking patients, equipment and staff in mass casualty events in their cases.

With the objective of enhancing patient flow efficiency, Kumar et al. (2009) simulated how RFID could help in improving service time especially for Waiting and Discharge in a hospital. Through utilizing RFID enabled information flow and patient electronic medical records, the waiting time was expected to have a 94% decrease for 20% of the patients due to better scheduling delivery room and equipment availability compared to the situation that there was no RFID used. In addition, the patients' discharge time was expected a 48% faster due to decreased paperwork and improved information flow. Chen et al. (2005) monitored the effectiveness of RFID system implemented in Observation Unit of Emergency Department by making a comparison between patients using RFID and those not using RFID. The result showed that the lengths of waiting for both acute bed admission and ICU admission have been reduced thanks to the application of RFID.

For the purpose of reducing medication errors, Nath et al. (2006) mentioned in their paper that information about a patient's medical history, dosage for an administered drug etc. could be associated with a RFID tag on patient. Reading the tag using a RFID reader could simply help eliminate various data entry errors or drug administration mistakes by medical workers' operational problem. Sun et al. (2008) actually designed a system called Wisely Aware RFID Dosage for protecting inpatient medication safety. In the system, the nurses use a PDA that functions as a RFID reader to scan patients' RFID wristband tags in order to make sure the right drugs match the right patients.

2.2 RFID Tracking Accuracy

By utilizing the reference tags, several literatures discussed the improvement of RFID tracking accuracy in their specific circumstances. Ni et al. (2004) proposed a novel system named LANDMARC for indoor localization using RFID technology. The LANDMARC is based on radio signal strength for localization and it proposed to introduce reference tags to help improve localization accuracy. Jin et al. (2006) suggested an enhanced method for calculating the position of tracked RFID tags based on the LANDMARC system. Instead of considering all reference tags while calculating target tag's location, only the necessary neighbor tags of the target tag are used for calculation. The improved method which is proved by experimentations results in an obviously reduced system latency and a faster speed for locating. For comparison with LANDMARC system, Reza et al. (2009) investigated a RFID indoor location sensing system based on the statistical averages algorithm for the tags' positioning. In the proposed algorithm, the tag's approximated coordinate is calculated by averaging the coordinates of all readers that detect the tag. The algorithm divides the area covered by all readers into two types, namely, unpaired zone and pair zone. The accuracy of the method depends on the placement of the reader antennas and the zone where a given tag locates. The error analysis had been done in comparison with LANMARC system.

A zone-based RFID localization technique (Khedo et al., 2010) was proposed to estimate the tags' location without using Radio Signal Strength Indicator (RSSI) that is usually required by other common localization techniques. By purposefully creating extra overlapping detection zone of two RFID readers, 5 different zones including 2 overlapping zones can be formed by using 3 readers. Several groups of experiments have been conducted to decide the best distance of placement between readers. The principle of the technique is that a given tag can be located approximately in a certain zone by analyzing which reader and how many readers successfully detect the tag. Another localization technique (Khedo et al., 2010) that does not require the RSSI is Time-based distance estimation (TBDE). The time of the signal transmitting from a tag to readers are calculated and used for calculating the distances between the target tag and different readers. As the locations of different readers are known in advance, the position for the target tag then can be determined by mathematical methods.

Ganz et al. (2010) introduced the framework and localization principle of a RFID based real-time tracking and localization system called DIORAMA which is intended to be used for outdoor mass casualty incidents. With the help of the system, the triage of patients can be done more rapidly and all patients as well as emergency staff is also tracked and located in real time. The system uses the RSSI fingerprint method to localize people. The incident area is first uniformly divided into small grids for which the values of expected received signal strength from every reader are defined. Furthermore, the average signal strength is calculated by averaging the signal strength readings of the tag on a tracked person. Finally, the system can match the signal strength value of the tag with the most proximal predefined signal strength value of certain grid and the estimated location of the person can be determined.

2.3 Unreliable Reading Elimination

The unreliability of RFID systems in data collection is represented in three different cases, namely, duplicate readings, false negative readings and false positive reading. The problems have attracted many researchers' attention. Different approaches have been proposed to tackle the problems. These approaches can be classified into two different categories (Liu et al., 2010). One is from the perspective of RFID data flows by adopting smooth mechanisms, the other one is from the perspective of applications by using different integrity constraints.

To give a clear overview of the RFID data processing procedure, Liu et al (2010) classified the whole RFID data processing procedure into three different layers based on the types of data errors. Each layer has its own specific mission to clean a specific type of error data. In its simple event processing layer, redundant data is cleaned by unduplicated constraints. The processed data then comes to the second layer which is called the complex event processing layer and will be further cleaned by eliminating the false negative and false positive data. The method for eliminating false negative and false positive readings is based on the route integrity constraint.

To duplicate reading elimination, Mahdin et al. (2011) proposed a new approach for removing redundant data from RFID data streams. The proposed approach focuses on reader level redundancy rather than on data level where many other comparable approaches concentrate. Duplicate readings at the data level mean a given tag is read by a single reader recurrently, while duplicate readings at the reader level refer to a given tag is read by multiple readers with overlapped read range at the same time. The proposed Comparison Bloom Filter algorithm is used for solving the duplicate data problem at reader level. In the algorithm, the number of readings from different readers but for the same tag will be compared with the help of a hash function, and the highest number of readings will be kept in the hashed counter which means the tag is in the vicinity of a reader with the highest number of readings on that tag.

A popular approach to eliminate unreliable RFID readings is based on the slide window algorithm. Some variants of the sliding window-based technique are proposed (Jeffery et al., 2012, Bai et al., 2006, Mahdin & Abawajy, 2010, Ku et al., 2012, Fan et al., 2012, Jiang et al., 2011).

Conventional sliding window technique defines a static window size for the lifetime of the system. The static window size might cause more false negative or false positive readings depends on the different application environments. However, Jeffery et al (2012) proposed an adaptive smoothing filter termed SMURF that can adaptively adjust the window size in order to fit more application environment. By observing readings as unequal-probability random sample of tags, SMURF can distinguish between tag movement events and missed readings, which the conventional solutions cannot.

A Streaming Bayesian Inference approach is also proposed for real-time data cleaning. Ku et al (2012) firstly developed an n-state detection model by dividing a reader's detection region into n different zones based on the different reading rate of each zone. Then the model was incorporated with the Bayesian inference and the Metropolis-Hastings sampler for the purposes of calculating likelihood and sampling. At last, combining with sliding window, the algorithm can efficiently clean RFID data.

Jiang et al (2011) proposed a communication protocol based on the ability of communications between RFID readers. They assumed that a RFID reader could inform other readers its reading situation for references. Thus, a set of protocol was designed to define the communication behaviors of readers. Based on the information sharing among readers and necessary probabilistic inferences, correct readings can be found and false readings can be eliminated using sliding window method.

Fan et al. (2012) utilized the kinematic characteristics of tags to clean the RFID data. Tags movement behaviors can reflect on the changes of reading rate sequence. Besides the proposed algorithm, a Reverse Order Filling method was used for further improving the accuracy of data cleaning by reversely filling the missed data again without scanning all data from the beginning. They proved that the proposed algorithm performed better than the sliding window method on precision.

Song et al (2009) proposed a variant of smooth filter named BSpace to clean RFID data. An initial set of data records was formed by setting classified tags move along possible paths. Tags with the same track were merged into the same group called Virtual Spatial Granularity. The false readings were filtered out if the corresponding track of the reading cannot match any of the existing ones in the spatial granularity categories.

Considering the limitations of current methodologies for false positive problems, some researchers attempted to use intelligent methods to solve the problems. Darcy et al. (2013) proposed an intelligent method with integrating three different intelligent classifiers for classifying raw RFID data. After the first phase in which the suspicious reading is found by applying some defined rules, the characteristics of the suspicious reading will be used as the input for three intelligent classifiers which are Bayesian Network, Neural Network and Non-Monotonic Reasoning. Any of three classifiers is able to determine if the suspicious reading should be kept or discarded before the final change of RFID database in the last phase.

A machine learning-based approach is proposed only for solving the false positive RFID tag readings (Keller et al., 2010). Based on the low-level reading data collected, the distribution of the standard deviation of the Received Signal Strength Indication (RSSI) values for both correct and false tag readings is depicted and the RSSI value threshold to separate correct and false tags then can be obtained by calculating information gain which is a common method in machine learning. Thus, the false positive readings can be identified and deleted by comparing with the threshold.

Scholz et al. (2011) first compared four different machine learning algorithms in terms of their overall performance on the prediction accuracy for room-level RFID localization. With the environment of a two-hour poster session on a conference, a RFID system with six readers and numerous reference tags were placed in five adjacent rooms. It was proved by the experiments that more sophisticated algorithms outperformed less sophisticated ones. In addition, as the tags used in the experiments were able to provide information of not only tag ID but also other tags nearby, therefore, they utilized the contact information between tags to further boost the accuracy. The additional experiments verified the significant improvement in the prediction accuracy when incorporating contact information into the machine learning algorithms.

Moreover, Parlak and Marsic (2011) mainly used two methods in his experimentation on improving the RFID accuracy for an operating room of a hospital. The first method is a relatively coarse algorithm for localization which is termed as zone-based while the other one is a finer algorithm which utilized k-Nearest Neighbors (kNN) algorithm by comparing the target’s signal strength to the predefined radio map. In the zone-based localization, four different machine learning algorithms (classifiers) were used for comparison and two indicators, namely, Radio Signal Strength Indicator (RSSI) and the Read Rate were used for the accuracy measurement. The results in this method showed the Bayesian Filtering outperformed other algorithms in terms of RSSI. In addition, the combination of coarse and fine localization methods was also conducted in the experiment and showed better accuracy than only zone-based method. Finally, they evaluated the performance of these localization methods under more complicated and closer to reality environments such as environment with human movement and occlusion as well as multi-tag scenario. It was found that the accuracy of zone-based and kNN was even improved with human movement as the human body as a barrier between zones could stop reflected signals going to other zones by absorption.

In addition, different application environments of RFID systems have their own environmental constraints such as the situation of overlaps among readers, the practical detection performances of different readers or the maximum number of tags that possibly reside in a reader's coverage area. The environmental constraints for a specific application should be taken into account seeing that the characteristics of the constraints would greatly assist in improving the effect of data cleaning (Fan et al., 2012). Other research has taken the environmental constraints into consideration incorporated with their proposed data cleaning algorithms (Fan et al., 2012, Tu & Piramuthu, 2008).

2.4 DOE in RFID System

The tracking accuracy can be improved through applying DOE optimization method as a system that is not well configured only produces random performance that is usually not satisfactory. Most of the literatures that studied the application of DOE on RFID systems are in packaging, library and transportation settings.

Mapa et al. (2010) evaluated the effect of nanofluids on the readability of RFID tags. The experiments were designed with the nested factorial design model to study factors' effects on the tag readings. The analysis of variance (ANOVA) results showed that the speed of the conveyor and the fluid types are significant factors. Instead of using nested design, a 2^k factorial design was adopted by (Aryal et al., 2010, Kabadurmus et al., 2007, Wang & Wang, 2010) to test the effect of factors such as conveyor speed, product type, tag orientation, etc., on the performance of a RFID system in a packaging environment. ANOVA was used by all these research to analyze the experiments. Wang and Wang (2010) also found that the best system performance can be obtained by setting the conveyor speed at 1.5m/s instead of the lowest level, which is not expected by previous studies. Huang and Chang (2007) studied four factors related to a RFID controlled delivery track using a L_9 experiment that is based on orthogonal array. Similarly, a partial factorial design based on orthogonal array was carried out by Hur et al. (2009) for a RFID conveyor belt system. They went one step further to build a predication model using the experiment results. They proved that a neural network based predication model was better than the conventional analytical model in terms of both accuracy and predictability.

Another major RFID application area where DOE is applied is in a library environment. Golding and Tennant (2011) and Hui et al. (2013) both used 2^k factorial design for evaluating the effect of factors on the performance of a library inventory system. With only the significant factors and their interactions, the response (average strength) equation and surface plot were built by Hui and Luk (2013) for finding the optimal settings.

In addition, several studies have been done for RFID in transportations. An RFID-enabled Mile Marker System has been designed for identifying vehicle on highway before the vehicle reaches the weight checkpoint (Jones et al., 2010). He designed an experiment to find out the best settings for two factors that are antenna height and tag height, in order to get the best reading performance. Venkatesan (2011) conducted an experiment for evaluating the readability of a RFID system in static and motion testing by considering two factors that are materials of the license plate and the car speed.

In summary, the existing research mainly dealt with the RFID system in limited application areas. The application of DOE for a RFID system in a healthcare setting has not been found in the literature. Although some application areas share some common characteristics when being applied with DOE methodology, it is still very necessary to discuss the way to apply DOE for a RFID system in other obviously different application areas, for instance, the healthcare.

2.5 Sensor Data Fusion

To my best knowledge, there is very limited number of works in literature discussed about RFID and sensor fusion for personnel tracking. None of them talked about the healthcare application. A novel technique for indoor positioning which combines Inertial Measurement Unit with RFID system was proposed by Wong et al (2013). For the RFID part, the RSSI values of RFID tags are processed by Kalman Filter. For IMU part, two parameters, namely the linear accelerations and angular velocities, are used to calculate the updated coordinates of the tracked objects. Then the estimated position by IMU will be checked if it is falls within the acceptable region of RFID readers based on the RSSI value. If both parts agreed, the estimated position by IMU is accepted; otherwise the estimated position will be repositioned by shifted to the mid-point between the inner and outer peripheries of the acceptable region in the radial direction. The effectiveness of the technique is finally verified by an experiment study.

House and Connell (2011) described a food-mounted indoor localization system. The system consists of a gyroscope, an accelerometer, a magnetometer and a RFID reader. With the objective of reducing drift of IMU, the Extended Kalman Filter (EKF) and Zero Velocity Update (ZUPT) are implemented with the system. In this system, the velocity is reset to zero when there is a footfall for eliminating most of the drift in Zero-Rate Output (ZRO). In addition, several RFID tags are placed on the ground in commonly traversed locations as fiducial markers for the RFID reader tied on foot to read. The reference tags help remove drift caused by IMU. The footfalls trigger Kalman filter process to update estimates for position, velocity and orientation using IMU and RFID data.

2.6 Agent-Based Modeling

In the world of system simulation, there are three popular techniques, namely discrete event modeling, system dynamics modeling and agent-based modeling (Borshchev, 2013). Bonabeau (2002) addressed questions such as why ABM is useful and when ABM should be used. ABM captures emergent phenomena which results from the interactions of individual agents. Because of the interactions, the whole ABM system is more than the sum of its parts. ABM also provides a more natural way over other modeling techniques to model a system as it looks at an organization from the perspective of individual activities rather than business processes. Because of the characteristic of modeling individuals, the ABM model is very flexible to change and improve. The individuals in the model can have the ability of self-learning which makes the system intelligent and evolutionary. One of the application areas of ABM according to Bonabeau (2002) is flow management, such as traffic and customer flow. He studied the example of a theme park or supermarket and the effect of people's interactions.

Several simulation research has been done for healthcare environments. Laskowski et al. (2009) applied agent-based modeling to gain insight into the operations of an ED. Based on the basic aspects of an ED treatment process, which includes patient arrival, registration, triage, waiting, treating and discharge phases, the model provides an initial framework for understanding the relative sensitivities and impacts of the simulation parameters and for future required complexities and refinements. The model was also introduced to be used in optimizing the ED resources such as the staff allocation. Based on the model framework constructed, the evolutionary algorithms such as genetic programming and machine learning were incorporated with the model to optimize the patient waiting time and care policies through system evolution in a subsequent work by Laskowski (2013).

The uncertainties inherent of a RFID tracking system in ED are also studied in another work by Laskowski et al. (2010). An RFID real-time location system (RTLS) augmented agent based model was constructed as a tool to study the uncertainty. The model run with four different reader layout configurations based on reader density and the simulation results were compared with each other in terms of the reading error which was measured as the spatial error from the patients' actual position. The results showed that the error or uncertainty is clearly reduced as the number of readers increases.

2.7 Summary

The literature on the topics of RFID application in healthcare, algorithms for eliminating unreliable readings, DOE optimization on RFID system, sensor data fusion as well as agent-based modeling techniques have been reviewed in this chapter. For the objective of unreliable RFID reading elimination in this research, the sliding window-based smooth filter algorithm establishes the basis for the proposed algorithm that will be described in Chapter 4. However, as most of the data cleaning algorithms are based on Radio Signal Strength Indicator (RSSI) that is provided by the capable readers, this research proposes a read rate-based data cleaning algorithm that does not require RSSI.

For the RFID system optimization, none of the related works applied the DOE methodology in healthcare field. Although a couple of fields share some common characteristics with healthcare, there are still major differences such as choice of factors and design process in a healthcare environment when applying DOE, which needs to be tested by conducting actual experiments.

There is few work found for RFID and sensor fusion, especially in healthcare for personnel tracking to my best knowledge. No work has been found to use gyroscope to capture turning event for assisting RFID tracking.

The existing ABM model for healthcare discussed the simulation of the operations of ED and the uncertainty in a RFID enabled ED, which provides a very meaningful model framework for the proposed model. However, the proposed model focuses on the availability of the reading accuracy improvement features in the model, which was not addressed in the related models.

Chapter 3

System Setup

3.1 Introduction of Existing RFID System

All the RFID readers and tags used in this research are purchased from GAO RFID Inc., a RFID hardware and solution provider based in Toronto, ON, Canada. The readers are 2.45GHz Gain Adjustable Active RFID Reader as shown in Figure 3.1. The reader uses a built in Omni-directional antenna allowing it to identify transponder tagged items up to 100 meters in all directions. Users can adjust the identification distance from less than 5 meters to 100 meters according to actual situations in order to make identification more accurate. The reader uses an advanced 0.18 μm CMOS IC for ultra-low power consumption. The reader features optional built in PoE (Power over Ethernet) which is the ability for the LAN switching infrastructure to provide power over a copper Ethernet cable to an endpoint or powered device. The technical specifications of the reader model are shown in Table 3.1.

Figure 3.1 Reader Used in This Research (GAO RFID, 2.45 GHz Active RFID Reader, 2014)

Table 3.1 Technical Specification of Purchased Readers

Direction	Omni-directional, standard whip antenna
Range	0 to 100 m adjustable
Frequency	2.4 GHz to 2.5 GHz ISM (UHF-Ultra High Frequency)
RF Output Power	0 dBm
Sensitivity	-90 dBm
Power	50 mA, 9 V
Modulation	GFSK
Modes	Direct Mode and Buffering Mode. In direct mode, the reader uploads messages to the host system in real time. In buffering mode, the reader save messages, which are uploaded only when requested by the host system
Dimensions	126 x 104 x 28 mm
Data Rate	1 Mbps
Interface	TCP/IP (RS232 is optional) (PoE is optional)
Operating Temperature	-40 ℃ to 80 ℃
Operating Humidity	95% Non-condensing
Multi-Detection	100 tags/sec

The tags used in this research as shown in Figure 3.2 have three types, namely card tag, strip tag and wristband tag. They are all 2.45 GHz active tags with no difference in working mechanisms. The technical specification can be found in Table 3.2.

Figure 3.2 Tags Used in This Research (GAO RFID, RFID Active Tags - 2.45 GHz, 2014)

Table 3.2 Technical Specification for Purchased Tags

Read Range	0 to 100 m
Frequency	2.5 GHz ISM
RF Output Power	0 dBm
Power	12 to 18 μA, 3 V
Modulation	GFSK
Data Rate	1 Mbps
Anti-collision	100 tags simultaneously
Operation	Read only
Battery Life	More than 4 years

The RFID middleware as shown in Figure 3.3 is particularly customized for the SOGH ED RFID system. The program is written in C# language with Microsoft Visual Studio Development Environment. It consists of functions including tracking information, map view, replay and so on. The tracking information function is used to display all processed readings in a list. The map view shows the readings at corresponding locations on a map of MTA. Replay function is for replaying a person's tracking history. The program runs on a Windows OS Server dedicated for the RFID system.

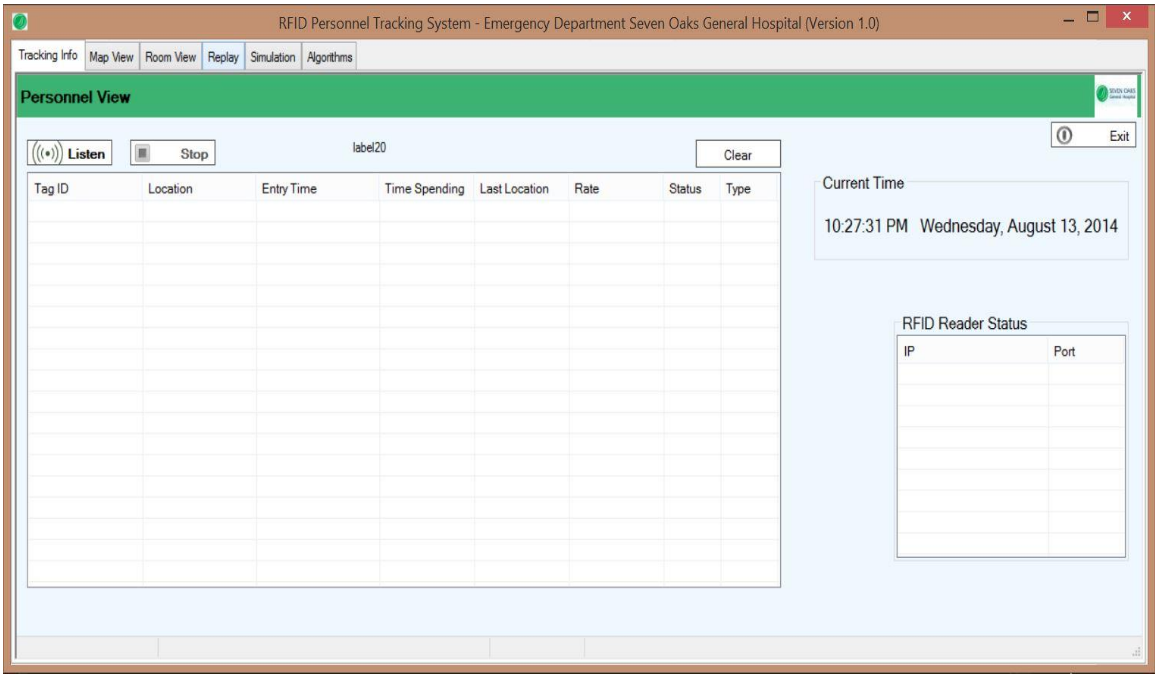


Figure 3.3 Customized RFID Middleware

3.2 Architecture and Environment

The structure of the RFID system in the hospital is shown in Figure 3.4. RFID readers are connected with a RFID server through a wired channel. The RFID middleware which is installed in the RFID server is used for processing raw reading data, storing and retrieving data via a RFID database. The RFID server also provides an interface for interacting RFID data with enterprise applications, such as Enterprise Resources Planning (ERP), Customer Relationship Management (CRM) and so on.

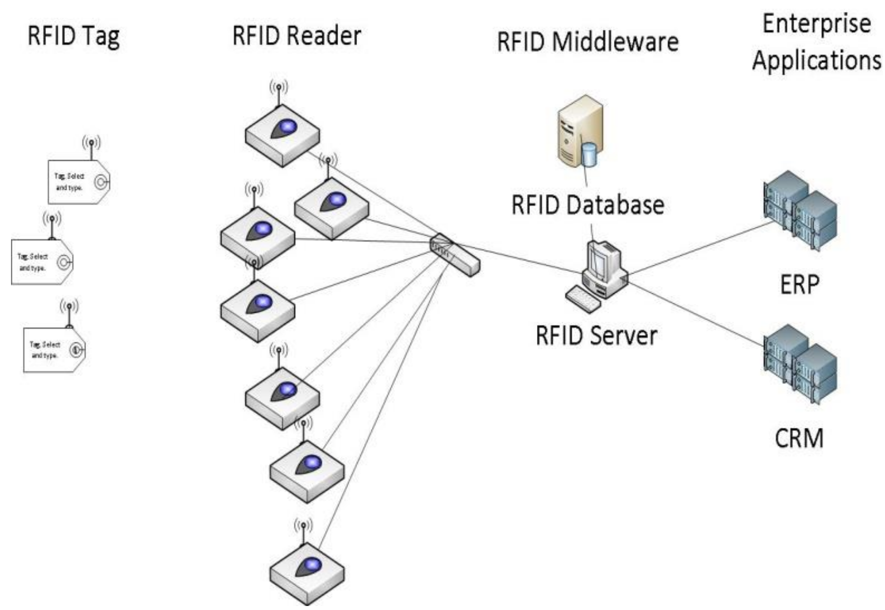


Figure 3.4 RFID System Architecture

The actual photos of MTA area in SOGH ED where this research is physically conducted are shown in Figures 3.5 and 3.6. There are five treatment rooms in MTA. Two entrances/exits are connected by one straight hallway. There is also a patient restroom, a storage room, a nurse practitioner area and a waiting area in MTA. The MTA floor plan is shown in Figure 3.7.

Figure 3.5 Minor Treatment Area

Figure 3.6 Reader in Treatment Room

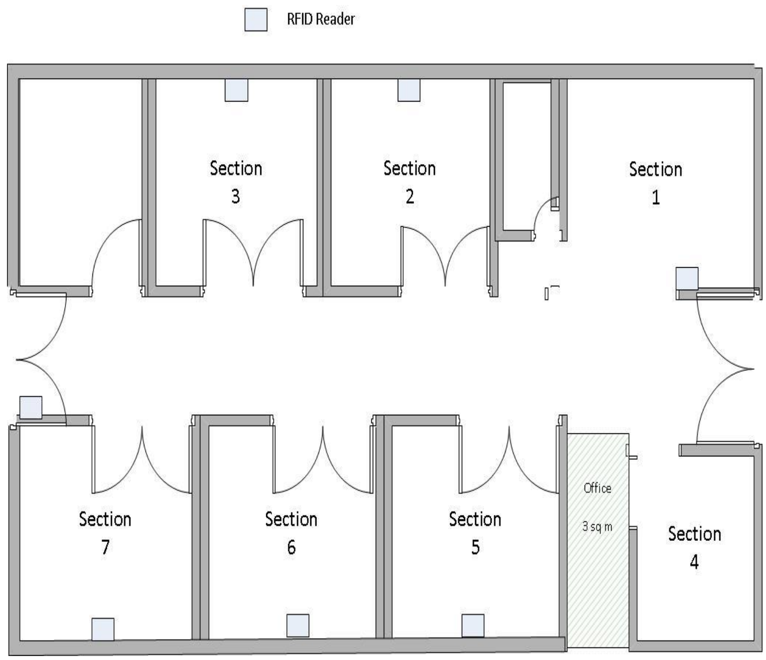


Figure 3.7 Layout of MTA

Chapter 4

RFID Data Cleaning

This part of research improves the RFID reading accuracy using an effective software algorithm. A reading rate-based algorithm is proposed to improve the RFID accuracy by eliminating duplicate and false positive readings (Bian et al., 2013). Considering the characteristics of the daily ED operation, the medical staff might stop at each treatment room for a period of time to check up patients. Hence, the interval for updating personnel tracking status should be as short as possible so that no person's movement event is missed out.

However, the algorithm will not be helpful in judging the personnel status changes if insufficient raw reading data are received. In other words, a short period of time, 5 seconds for example, can only allow the readers to receive very limited number of reading data, which is not enough for distinguishing false readings. Thus, the update interval is defined as 30 seconds in this case in order to guarantee a higher accuracy. The length of the interval can be modified to meet the different situation. The RFID middleware takes the responsibility of updating the tracking result every 30 seconds to let the user see a nearly real-time tracking result. At the end of each data gathering period, the RFID middleware will refresh the tracking status based on the data received during the last 30-second data gathering period.

4.1 Data Collection

The data collection takes place during workdays when the ED operates as usual. Thus, we guarantee the data to reflect the true situation in the ED. The actual location and path of a person are recorded manually for comparison with the RFID records. All RFID records received in the latest gathering period are firstly stored in a list waiting for the algorithm process.

4.2 Duplicate Reading Elimination

A 2-tuple <Tag ID, Reader> is used to classify readings. The reading records with the same tag ID and the same reader will be considered as the duplicate reading in the situation. Only the reading that is read for the first time will be added into the list. All subsequent readings with same tuple will be discarded and the count for that reading will increase 1. The pseudo code of the algorithm for eliminating duplicate readings is shown in Figure 4.1.

```
Algorithm: Duplicate Reading Elimination
INPUT: tag ID, location, rawTagList
OUTPUT: readings without duplicate
BEGIN
1: for each incoming reading do
      2:   if the 2-tuple <<Tag ID, Reader> of the reading
   does not exist in the rawTagList
3:    store the reading in the rawTagList
4:   else
5:    find the index of the existing tag
6:    increase the count attribute for the existing tag by 1
7:   end if
8: end for
END
```

Figure 4.1 Pseudo Code of Proposed Duplicate Elimination Algorithm

4.3 False Reading Elimination

A read rate-based data cleaning algorithm as shown in Figure 4.2 is proposed to tackle the false positive reading problem. There is a proven fact that the read rate of a tag on a reader is inversely proportional to the distance between the reader and tag, which means the nearer the tag is to the reader, the more frequently and stably the reader reads that tag. The linear relationship of read rate and reader-tag distance has also been experimentally proven in (Jeffery et al., 2012). Also, given that the RFID readers being used do not provide useful parameters for the tag distance calculation such as RSSI or Time of Arrival, using reading rate is the most direct and simplest way to determine the proximate location of a tag.

As the interval of request towards each reader by RFID middleware is set to 2 seconds, all readers would be requested to send data to the middleware 15 times in one data gathering period (30 seconds). If every request towards a reader is not null and there is always one reading on the same tag, the tag would be read by 15 times in 30 seconds in the best case.

Table 4.1 Sample Data for a Data Gathering Period

No.	Tag ID	Timestamp	Location	Rate (Count)
1	1	14:01	Section 1	15
2	2	14:01	Section 1	14
3	1	14:01	Section 2	3
4	3	14:01	Section 3	14

However, the practical case is that a tag might not be read by one reader for 15 times in every data gathering period due to interference by other equipment or person's movement, etc. The number of times of reading could be one or two times less but still very close to 15. As shown in Table 4.1 for a sample of a data recording, Tag 1 is read by the reader installed at Section 1 for 15 times according to the first record, while Tags 2 and 3 are both read by their corresponding readers for 14 times according to the second and fourth records respectively during the data gathering period. The second and fourth records are both regarded as the correct readings since their number of times of reading are very close to the ideal situation which is 15 times in the case. However, Tag 1 is also read by the reader at Section 2 at the same time and a reading count of 3 is recorded in the data gathering period, which is much smaller than 15, the ideal number of times of reading in the case as shown in the Table 4.1. Thus, we can confidently conclude that the third reading about Tag 1 is a false positive reading and Tag 1 at the time of reading was actually at Section 2 according to the manual record before the test.

Moreover, considering the situation that two readers both have read the same tag that is not within either of the readers' corresponding areas in a data gathering period and reading counts for the two readers are 3 and 5, respectively, we would choose the record with higher reading count of 5 as the correct reading and discard the other one based on the method described above. However, the assumed fact is that neither of the two records is correct and they are both false positive readings. In this case, a threshold to separate the correct reading with false positive reading should be set. Thus, the actual correct reading record should possess two characteristics. One is the number of times of reading in a data gathering period should be the biggest one among other readings for the same tag during the same time period. The other characteristic is that the number of times of reading should be equal or bigger than the threshold value to prove that it is not a false positive reading.

```
Algorithm False Positive Elimination
INPUT: tag ID, location, reading count, cleanTagList, threshold
OUTPUT: cleaned readings
BEGIN
1: for each Tag ID do
2:   find the reading with the highest reading count
3:   store the reading in cleanTagList
4:end for
5: for each reading in cleanTagList do
6:   if reading.count larger than threshold
7:      if cleanTagList contains any other reading with same Tag ID but different location
8:       then update the out time of the different location for the tag
9:       remove the other reading in the cleanTagList
10:    end if
11:      if cleanTagList does not contain any reading with the same Tag ID
12:   then add the new reading into the cleanTagList
13:   end if
14:  end if
15: end for
END
```

Figure 4.2 Pseudo Code of Proposed False Positive Elimination Algorithm

The current threshold is set based on the experimental experience. The threshold is currently set as 8 in the window size of 30 seconds. It is observed that some actual correct readings will be overlooked if the threshold is set too high, such as above 10 in the window size of 30. However, some actual false readings will be mistaken as the correct readings if the threshold is too low. Therefore, the threshold is temporarily set to 8 in the test. To mathematically calculate the optimal threshold, a statistical design of experiments method can be used to find the best and even global optimal threshold.

After the reads with highest reading count are selected, the next step is to put the reads into another list. At the startup of the RFID system, the first batch of reading data will be added in the list immediately. However, the readings in the list will not be deleted in the algorithm unless the person corresponding to a reading in the list changes its location which means there is tag movement event happens. The reason why the historic readings from the preceding data gathering period should be kept is that the historic data makes it possible to know the time that a person leaves certain section. This is realized by introducing location attribute of readings. When a new reading is added, the location attribute of the reading will be updated as the reader's corresponding section name.

If a similar reading with same Tag ID and reader ID comes in the next data gathering period, the algorithm will check in the list to see if there is a historic reading with the same Tag ID and reader ID. If there was, the location attribute of the new and the historic readings will be compared. If the location was not same, it explains that the corresponding person is in another section as the new reading indicated and the leaving time attribute of the historic reading will be updated. The historic reading will be deleted from the list at this time. The feature is necessary in the proposed false reading elimination phase because if the similar readings are only checked by comparing Tag ID and reader ID, the new reading with the Tag ID and reader ID all same with a historic reading will be viewed as a correct one while it is actually a false positive reading. With this mechanism, the person's movement can be identified and the false positive readings are avoided to some extent.

A false negative reading occurs when a tag is actually in the target area of a RFID reader but not detected by that reader. This type of reading is mainly due to collisions of a large number of tags. In the case of the local hospital, the false negative readings rarely occur because of the small number of tags. If any false negative reading happens in case, an inference mechanism can be used by comparing the results in the current window with the preceding scanning windows and the succeeding scanning windows. If the same tag has been detected during both of the preceding and succeeding windows, a reading can be considered as a false negative reading otherwise it is not. As the false negative readings rarely occur in the situation, it will not be discussed in details in this research.

4.4 Experimental Result and Analysis

To evaluate the proposed approach, we choose three tags from each of the three types of tags respectively in order to prove the availability of the algorithm for different types of tags being used.

Table 4.2 Experimental Tag Details

Group	**Location**
Group 1 (Tag IDs: 2714, 0246, 8087 in our experiment)	Section 1
Group 2 (Tag IDs: 0250, 2695, 8088 in our experiment)	Section 2

Table 4.3 Expected Results in Any 30-Second Period

No.	Tag ID	Location
1	0246	Section 1
2	2714	Section 1
3	8087	Section 1
4	0250	Section 2
5	2695	Section 2
6	8088	Section 2

Table 4.4 Raw Data Reading Results in a Random 30-Second Period

No.	Tag ID	Location	Count
1	0246	Section 1	15
2	0250	Section 2	15
3	0250	Section 5	3
4	2695	Section 2	12
5	2695	Section 5	9
6	2714	Section 1	15
7	2714	Section 4	1
8	2714	Section 7	2
9	8087	Section 1	14
10	8088	Section 2	12
11	8088	Section 5	3

Table 4.5 Clean Data Reading Results in the Same 30-Second Period

No.	Tag ID	Location	Count
1	0246	Section 1	15
2	2714	Section 1	15
3	8087	Section 1	14
4	0250	Section 2	15
5	2695	Section 2	12
6	8088	Section 2	12

The three tags form a three-tag group and two groups of three-tag are selected for testing in two different sections. Two interfaces in the middleware have been designed to show the raw and cleaned readings correspondingly for the test purpose. The details for the two test groups are shown in Table 4.2.

As shown in Table 4.4 for the readings during the experiment, 11 readings of different tags are observed during a 30-second period for example. The false readings are obviously included since only 6 tags are being used and each tag can only has one reading at a time if all tags do not move within the 30-second period. Therefore, some readings in the raw reading data set need to be identified and discarded.

After the filtration through the data cleaning algorithm, 6 readings in which each reading corresponds to its tag ID and location are obtained as shown in Table 4.5. All 6 reading are correct readings according to the experiment setup at the beginning which matches our expectation for the result as shown in Table 4.3.

The data cleaning algorithm shows its efficiency in filtering duplicate and false positive RFID readings. However, the algorithm runs under a random system setting which might not lead to an optimal clean performance. Hence, before the algorithm can be fully evaluated, the RFID system settings need to be optimized in order to create a best system environment for running the data cleaning algorithm.

Chapter 5

RFID System Optimization

It has been found during the initial system test that the system reading accuracy may be affected by different factors either from system or environment. An example of the effect from the system would be that the read range overlaps between readers 6 and 7 shown in Figure 1.2. The overlaps may strengthen or weaken radio propagation unpredictably as the influence also intertwines with the effect from environment. Environmental factors such as walls in the room and people' movements may cause the multipath of radio propagation and affect the read range in a random manner. People's movement may also affect the radio waves. Ten people moving in the area may make the reading accuracy different than none in the same area.

Therefore, the factors related to the system have to be studied and the RFID system should be optimized by artfully tuning the system parameters according to the application environment so that a better reading accuracy can be achieved. Otherwise, one will get a random system performance that might be full of false or duplicate readings and obstruct the application of data cleaning algorithm, which are usually below users' expectation.

To optimize a system, the experiment is always a method especially when the scientific phenomena is not regularly shown and well understood (Douglas, 2013). In fact, there exist some mathematical models which have been proven that too few factors were considered or the model might not valid when applied in industrial conditions (Hur et al., 2009). The Design of Experiments (DOE) methodology in this case is the best approach to study performance of this kind of system.

5.1 Response Variable and Factors

As the objective of this study is to propose a model for the RFID tracking system used in healthcare to find the system's best configuration, the indicator for evaluating how well the system is configured will be the reading (tracking) accuracy which is also the primary concern by decision makers in healthcare. Then the reading accuracy is selected as the response variable in the following experiments.

For the choice of factors, every possible factor related to the RFID system should be considered at first. A brainstorm should be undertaken with the purpose of obtaining as many factors as possible. The possible ranges and levels of each factor should also be listed. A fishbone diagram in Figure 5.1 shows all factors initially selected. However, not every initial selected factor can be considered in the final experiments due to the importance of factors and the cost of experiments. The factors considered in this research are not exactly like those considered in the packaging or library environment as hospital environment is a larger and opener area where more readers with higher frequency are being used. Therefore, the read ranges of all readers have to be considered here as factors for testing the effect of different combination of read ranges on the reading accuracy. In terms of tag related factors, they are highly unpredictable and uncontrollable as a patient affixed with a tag would probably move as he wants. Hence, the tag related factors highly depend on an individual patient. Thus, these unpredictable factors are treated with a random manner in the experiments so that the experiment results can be robust and work for any random situation. In summary, the read range of each reader will be considered as one individual factor in the final experiment.

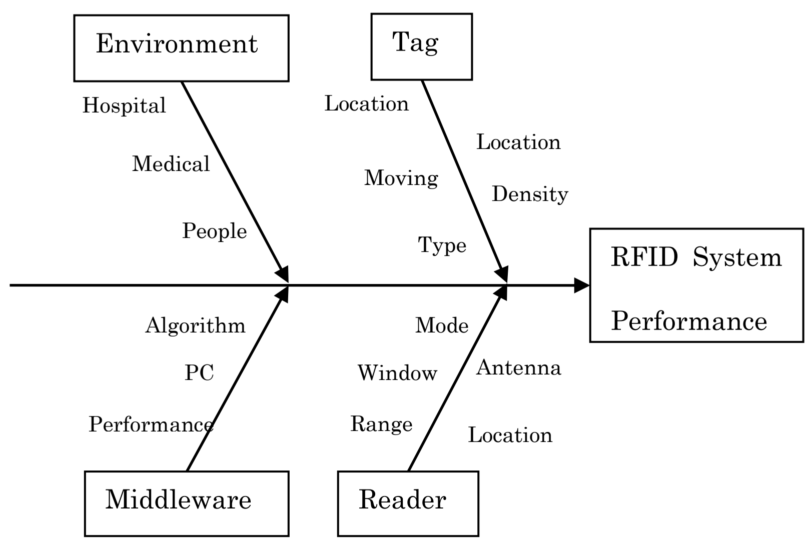


Figure 5.1 Fishbone Diagram for Factors Selection

The details about the final factors and levels can be found in Table 5.1. dBmW is used as the unit of measurement of radio power. By adjusting the radio power of a reader, the read range of the reader will be accordingly changed.

Table 5.1 Factors and Levels of the 2^4 factorial design

Factor	Levels
Read Range of Reader at Front Door	10dBmW, 20dBmW
Read Range of Reader at Rear Door	5dBmW, 15dBmW
Read Range of Reader in Room 25	5dBmW, 10dBmW
Read Range of Reader in Room 22	5dBmW, 15dBmW

5.2 Experiment Environment

An actual onsite experiment has been conducted in MTA of SOGH ED. Four readers installed in two treatment rooms and two entrances respectively are used in the experiment. Each reader in a specific treatment room is designed to be responsible for the patient tracking within that room. Similarly, two readers near the two doorways are responsible for the doorways each respectively.

As the experiments were conducted during the regular hours of ED, patients might come into any of the treatment rooms at any time during the actual experiment. Therefore, the experiment in a specific room should be terminated due to patient privacy reason once a patient occupied that room.

5.3 Experiments Setup

A 2^k full factorial design, where k is the number of factors, is carried out. There are 2^k combinations of factor levels. To fulfill three principles of a convincing DOE that are replication, randomization and blocking, each combination has three replications to make it $3*2^k$ runs in total, and all runs are tested in a random order. A single replicate of a complete factorial experiment is run within a block. All runs are equally divided into three blocks with 2^k runs in each. The hypothesis for this experiment is to test whether the different read ranges of readers have different main and interaction effects over tracking accuracy. The statistical design of experiments package MINITAB is used in designing and analyzing all experiments in this research. The Confidence Interval used throughout all experiments is 95.0. The readers send readings through wired channel to the middleware every two seconds. As the readings received might contains duplicate and false readings, the middleware collected all readings for 20 seconds for data filtering use. The data filtering algorithm has been discussed in Chapter 5.1.

5.4 Result and Analysis

The data is collected using a customized RFID middleware with the data cleaning algorithm discussed in Chapter 4 and analyzed using Minitab 16 Statistical Software. The response variable of the model as discussed above, reading accuracy is calculated as the proportion of the number of correct readings on a specific tag to the number of all readings on the same tag within a certain period of time.

Figure 5.2 shows the ANOVA output of this model based on data collected shown in Table 5.2. From the output, it can be interpreted that the read range of the reader in Room 25 and the interactions between the read range of the reader at front door and back door, reader at front door and reader in Room 25, reader in Room 25 and 22 all have significant effects on the reading accuracy as their p-values are all smaller than 0.05 which is the significant level of the test set before the experiments were conducted.

Analysis of Variance for Response (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	595.92	595.92	148.98	5.10	0.003
R-Front	1	450.19	450.19	450.19	15.41	0.000
R-Back	1	88.02	88.02	88.02	3.01	0.092
R-25	1	3.52	3.52	3.52	0.12	0.731
R-22	1	54.19	54.19	54.19	1.86	0.183
2-Way Interactions	6	2096.63	2096.63	349.44	11.96	0.000
R-Front*R-Back	1	136.69	136.69	136.69	4.68	0.038
R-Front*R-25	1	581.02	581.02	581.02	19.89	0.000
R-Front*R-22	1	0.19	0.19	0.19	0.01	0.937
R-Back*R-25	1	4.69	4.69	4.69	0.16	0.691
R-Back*R-22	1	1250.52	1250.52	1250.52	42.81	0.000
R-25*R-22	1	123.52	123.52	123.52	4.23	0.048
3-Way Interactions	4	411.58	411.58	102.90	3.52	0.017
R-Front*R-Back*R-25	1	72.52	72.52	72.52	2.48	0.125
R-Front*R-Back*R-22	1	0.52	0.52	0.52	0.02	0.895
R-Front*R-25*R-22	1	266.02	266.02	266.02	9.11	0.005
R-Back*R-25*R-22	1	72.52	72.52	72.52	2.48	0.125
4-Way Interactions	1	4.69	4.69	4.69	0.16	0.691
R-Front*R-Back*R-25*R-22	1	4.69	4.69	4.69	0.16	0.691
Residual Error	32	934.67	934.67	29.21		
Pure Error	32	934.67	934.67	29.21		
Total	47	4043.48				

Figure 5.2 Analysis of Variance for Response (coded units)

Table 5.2 Design Model and Data Collection

Standard Number	**Factors**				**Replicate 1 (%)**	**Replicate 2 (%)**	**Replicate 3 (%)**
	Reader Front	Reader Back	Reader 25	Reader 22			
1	-1	-1	-1	-1	79	90	79
2	1	-1	-1	-1	79	82	85
3	-1	1	-1	-1	77	83	75
4	-1	-1	1	-1	63	75	67
5	-1	-1	-1	1	67	56	54
6	1	1	-1	-1	75	65	63
7	1	-1	1	-1	85	92	85
8	1	-1	-1	1	69	69	71
9	-1	-1	1	1	58	71	71
10	-1	1	-1	1	73	87	85
11	-1	1	1	-1	63	67	62
12	1	1	1	-1	81	87	73
13	1	1	-1	1	73	83	81
14	1	-1	1	1	71	75	81
15	-1	1	1	1	83	75	73
16	1	1	1	1	87	85	83

The cube plot for response in Figure 5.3 shows the best reading accuracy (87.33%) can be achieved when the read range of both reader at Room 25 and reader at front door were set to their high level, in this case 15 dBmW while the read range of both reader at

Room 22 and reader at back door were set to their low level. The best combination of factor levels is shown in Table 5.3.

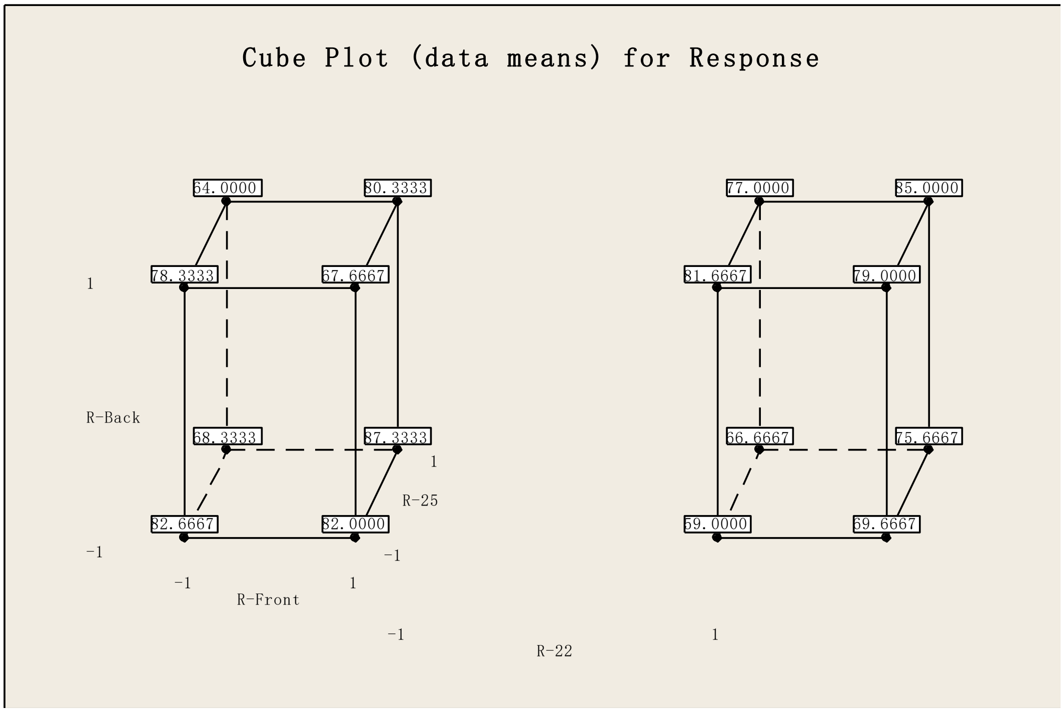


Figure 5.3 Cube Plot for Response

Table 5.3 Best Combination of Read Range Settings

Reader Location	Read Range (dBmW)
Front Door	20
Room 25	10
Room 22	5
Back Door	5

5.5 Model Adequacy Checking

Model adequacy checking is a procedure in DOE to check if there is any problem in the experiment process in order to see if the model is adequate and valid. The Normal

Probability Plot is used to check if all the data follows the normality assumptions. The normal plot in Figure 5.4 shows no major violation of the normality assumptions as most of the residuals fall close to the normal probability line. The Residual versus Fits Plot in Figure 5.4 shows no obvious pattern which means the variance of data is constant. The Residual versus Order Plot in Figure 5.4 shows that each run of the experiments is independent to each other and randomly conducted, which can make sure that there is no obvious influence derived from previous runs on the subsequent runs.

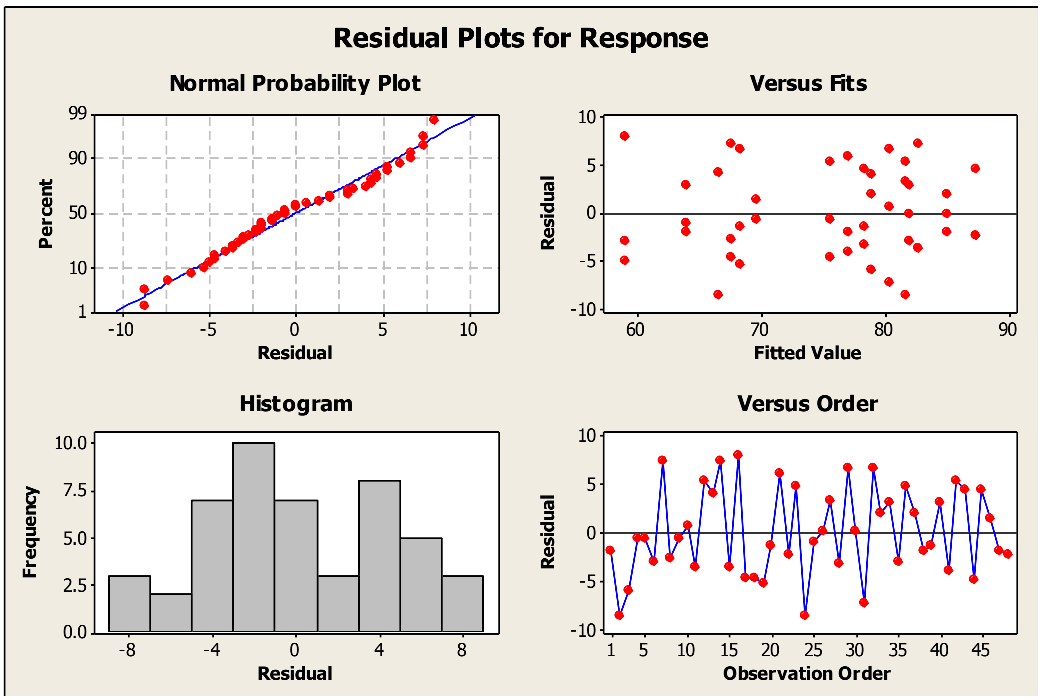


Figure 5.4 Residual Plots for Response

The Residuals versus Readers Plot shown in Figure 5.5 – 5.8 shows that the data from low and high levels both have constant variance and no unusual pattern has been found. In summary, as no unusual pattern has been found in the Residual Plots for Response, the model adequacy is validated and the model is satisfactory.

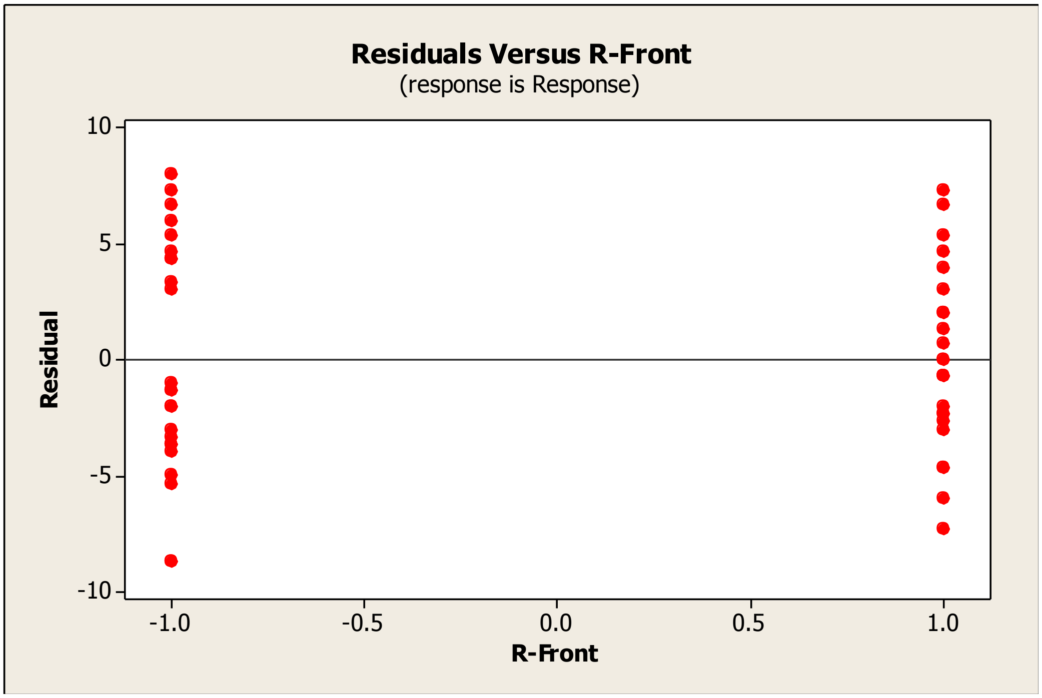


Figure 5.5 Plot of Residuals versus Read Range of Reader at Front Door

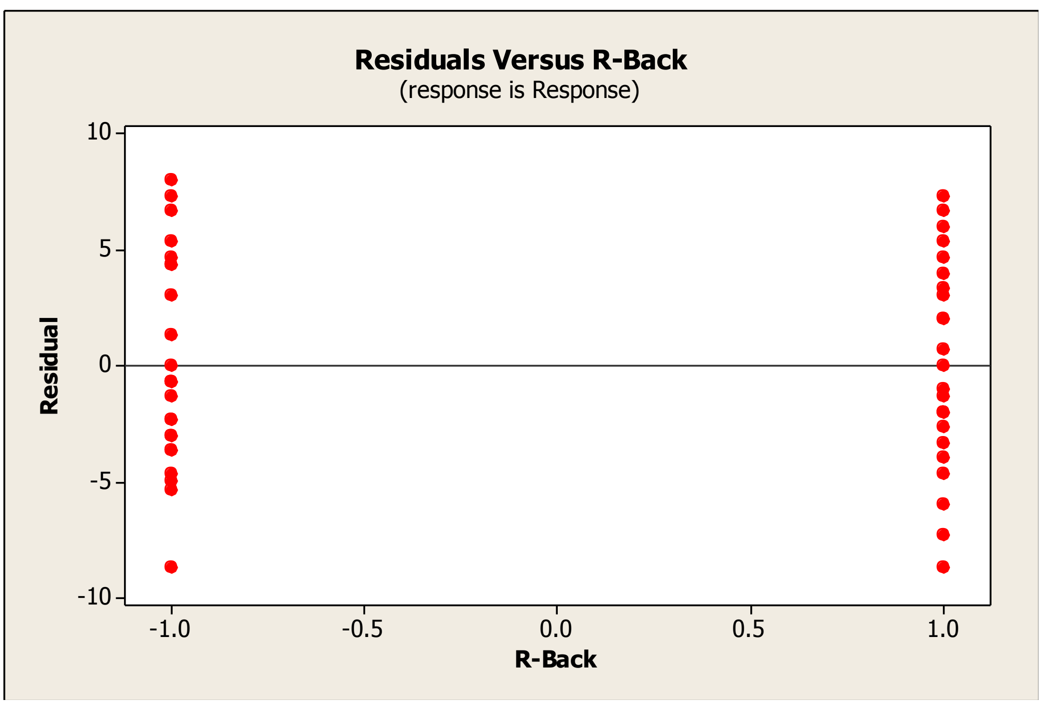


Figure 5.6 Plot of Residuals versus Read Range of Reader at Back Door

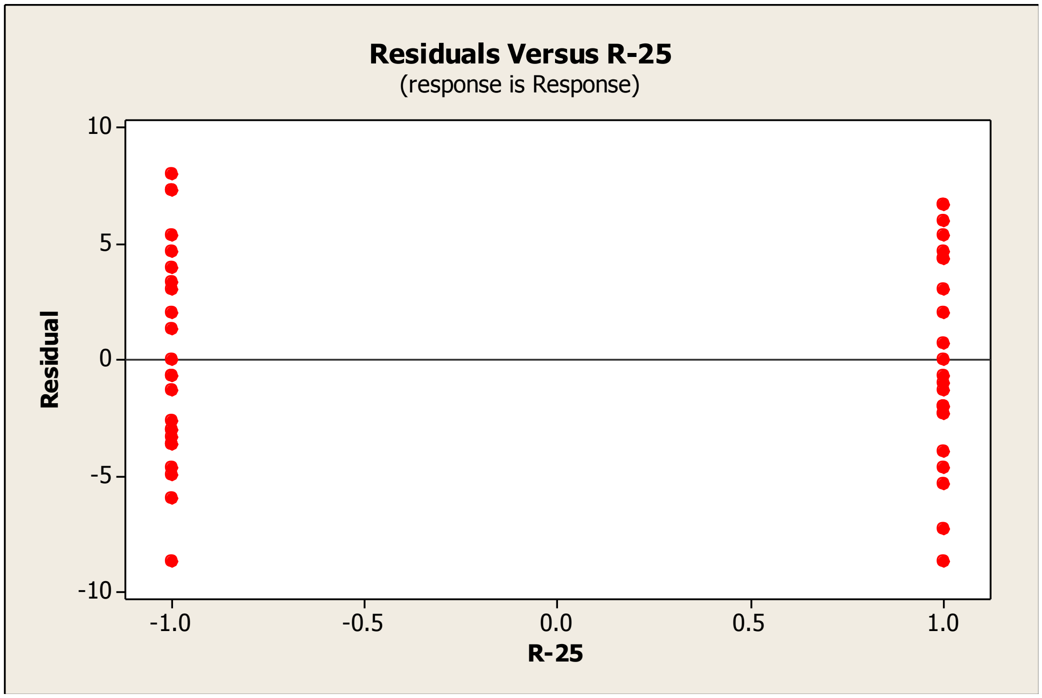


Figure 5.7 Plot of Residuals versus Read Range of Reader at Room 25

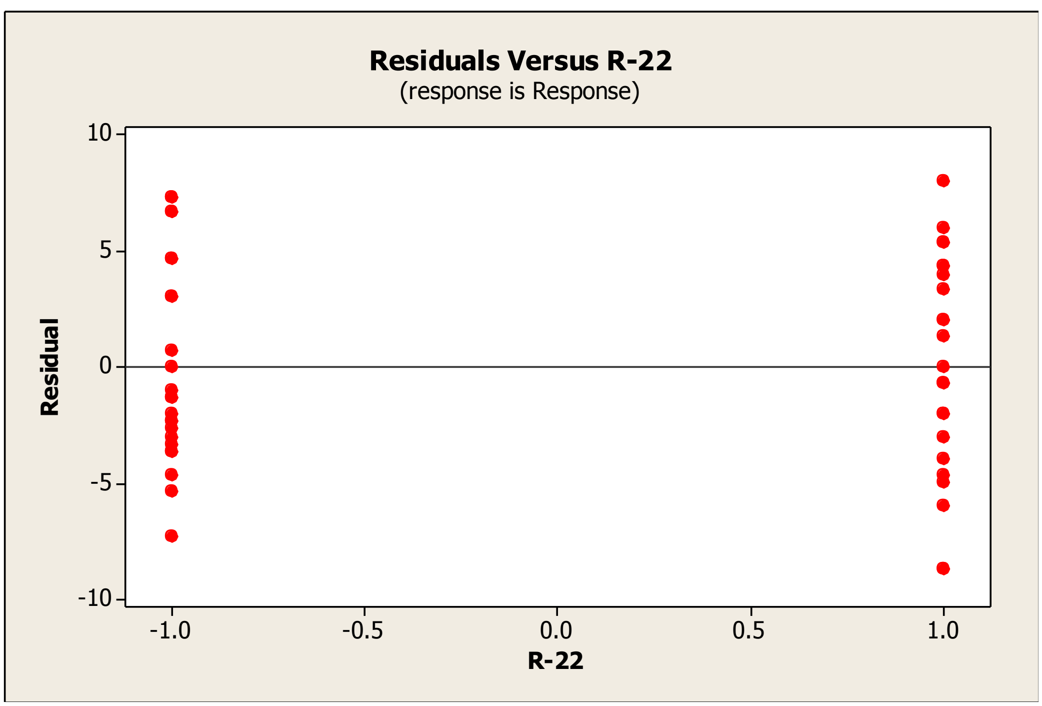


Figure 5.8 Plot of Residuals versus Read Range of Reader at Room 22

Chapter 6

Data Fusion

It has been discussed in Section 2.1 that the false positive readings could occur when the tagged person just passes by a room but does not enter into it. If the passing by behavior can be discerned from entering behavior, this type of false positive reading can be eliminated.

It is noticed that the most obvious difference between these two behaviors is turning. When a person is walking on the hallway in Figure 1.2, he has to make a turn to enter into any room. To capture a turning event, the gyroscope sensor comes into the field of vision. Data from sensors gains more and more applications these years. This includes fusing sensor data with the RFID data to help increase indoor localization. However, one big challenge of RFID and sensor data fusion is how to match the sensor data with RFID data. For this application, when a person is walking in the hallway and a reader detects the person, how to use gyroscope data to help RFID system identify a false positive reading is the problem going to be explored. Therefore, some research has to be done to tackle this problem.

Based on the current development of RFID technology and the ED environment, there is not much measures can be implemented to the RFID system itself besides the proposed two methods to improve the tracking accuracy. However, other technologies are recommended to be used and combined with the existing RFID system, thus another data source will be available to assist the RFID data for further refining the reading accuracy. A pilot study has been conducted in Auto-ID Lab at Massachusetts Institute of Technology to evaluate the availability of fusing another data source into the RFID data.

6.1 Experiment Setup

We started by a simple scenario which is shown in Figure 6.1. In this scenario, there are two adjacent rooms equipping with one Impinj Speedway Revolution UHF RFID reader, two Laird PA9-12 Antennas and a couple of Alien Squiglette passive tags as shown in Figure 6.2 – 6.5. A volunteer affixed with a RFID passive tag walks by following three different paths as described in Table 5.4. The purpose of creating three paths is to verify if the method works for different walking situation. When the volunteer is walking, he is also holding a Samsung Google Nexus S smartphone with a 3-axis gyroscope sensor loaded. The reason to use gyroscope sensor data as another data source is that it is simple to capture turning events, and by capturing turning events, the sensor data fusion technology could be verified to help recognize if a walking person is entering into a room or just passing by it. As some false positive RFID readings emerge when a person is just passing by a room but not entering, and the read rate-based data cleaning algorithm still shows some flaws in filtering false readings, this study is worth trying for further improving the tracking accuracy. This is the objective of this study.

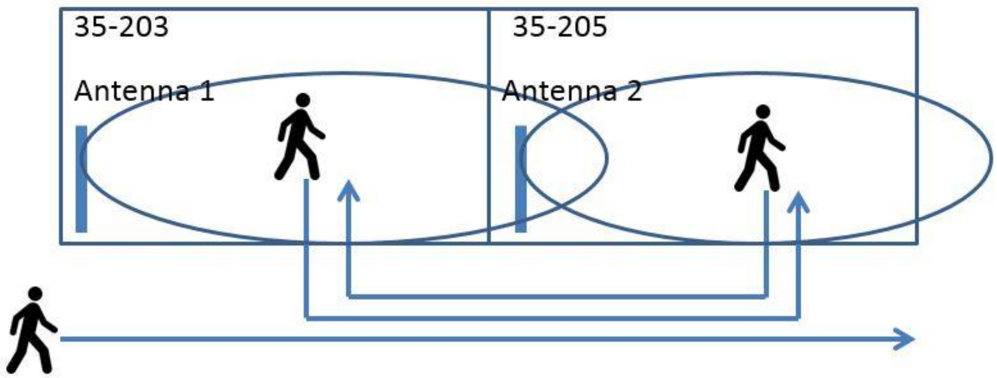


Figure 6.1 A Simple Scenario for Sensor Fusion

Figure 6.2 Antenna in Room 35-203

Figure 6.3 Antenna in Room 35-205

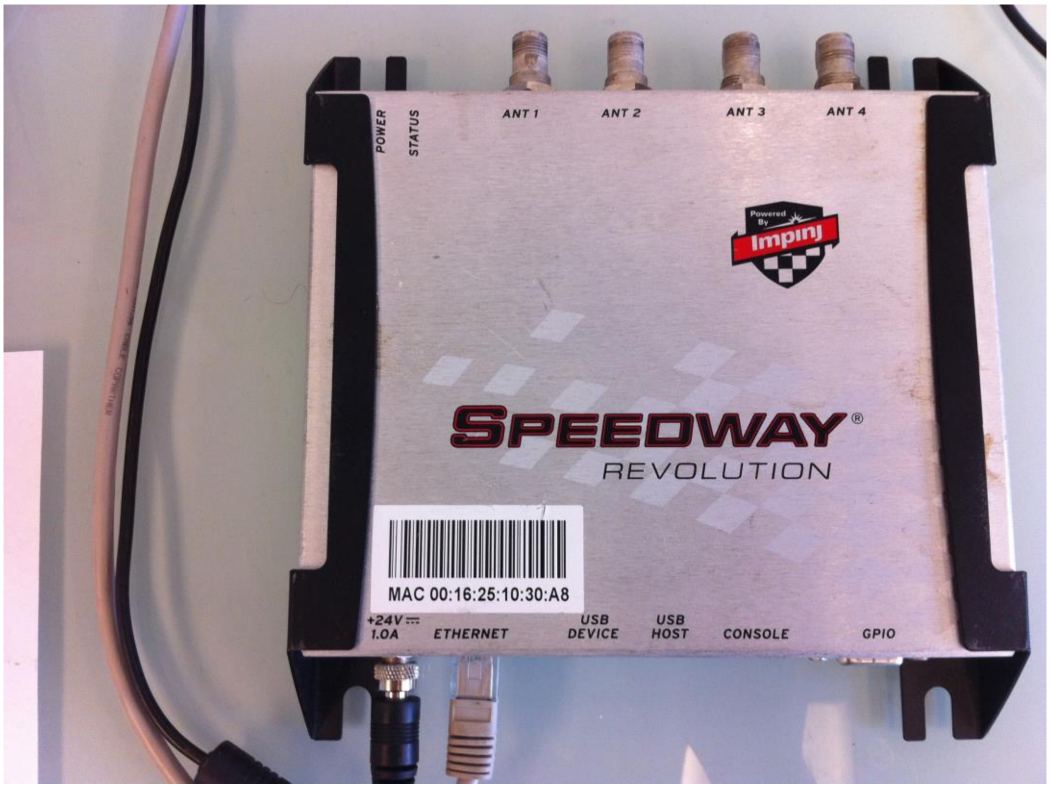


Figure 6.4 UHF RFID Reader by Impinj Speedway Revolution

Figure 6.5 Alien passive RFID tag

Table 5.4 Walking Path for Experimentation

Path No.	**Start**	**End**
1	Room 35-205	Room 35-203
2	Room 35-203	Room 35-205
3	Hallway by room 203	Hallway by room 205

6.2 Result and Analysis

The result analysis is done by trying to match the RFID data with the gyroscope data within the same period of time. Data from both sources are recorded with the same start time for synchronization purpose. All result plots are shown in Figure 6.6 – 6.11. A turn event is very easy to be found as it is represented by either an upward peak or a downward peak on the gyroscope plot. In order to match the RFID data plot with the gyroscope data plot, a turn that is associated with a room entry or leaving event has to be found at first. The next step is to calculate the time elapsed from the start and try to match the corresponding spot on the RFID data plot. If there is also an obvious change in RFID data flow and the change match the person's movement that is estimated from the gyroscope data source, it can conclude that the sensor data has successfully fused into the RFID data and is able to help identify the false positive reading.

Figures 6.6 – 6.9 are from the test results of Path 1 and 2 where there are turns occurred in the test. The results from Path 1 test are used as an example to interpret the results. From Figure 6.7 the first obvious downward peak appears at the 4th second from the timer starts. This means there is a turn occurs along the path, which indicates that the tester just exits the Room 35-205 and be ready to go to another room. It can be expected that the Antenna 2 in Room 35-205 should not read the tag on the tester after the turn event occurs. This expectation matches the RFID data plot in Figure 6.6. In addition, the results from Path 3 are shown in Figures 6.10 – 6.11, the RFID data are expected not having an intense continuous read on the tester's tag since there is no turn in the Path 3. From Figure 6.10, it can be found that there are only discrete reads on the tag during the test period. Therefore, it can conclude that these discrete readings are false positive. The tests verified the effect of data fusion in eliminating false positive readings.

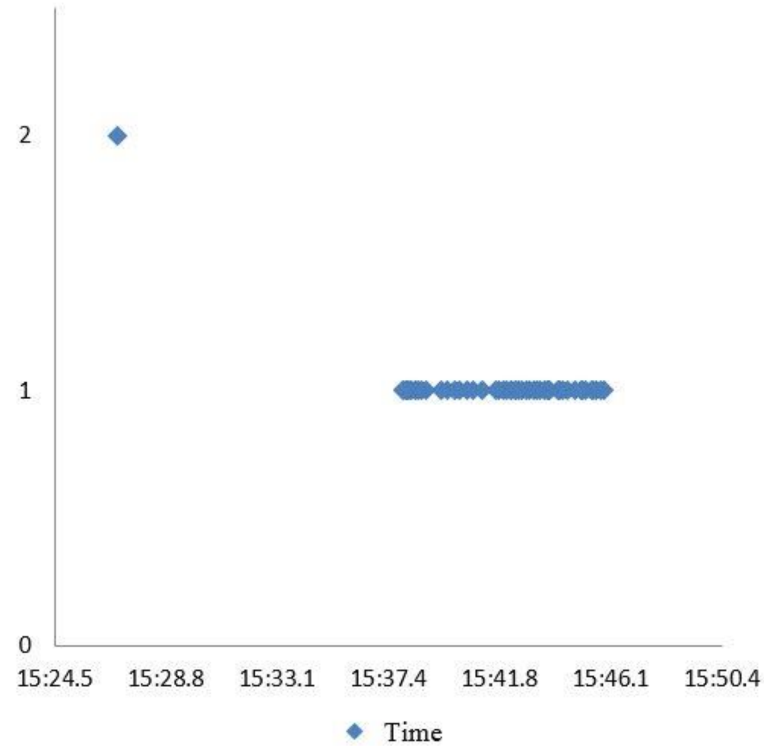


Figure 6.6 RFID Data for Walking Path 1

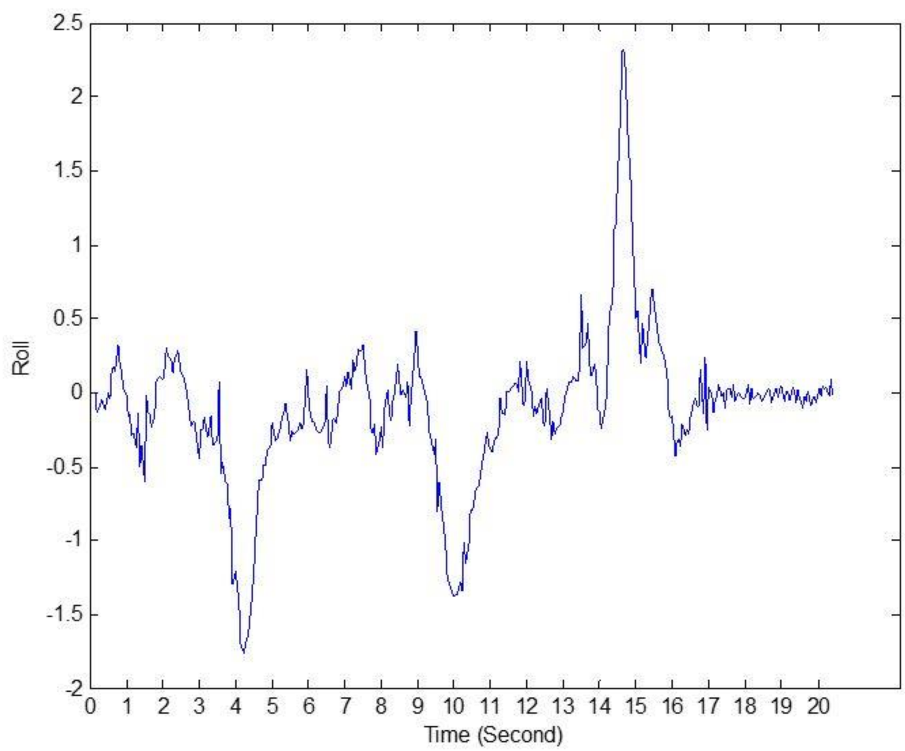


Figure 6.7 Gyroscope Data for Walking Path 1

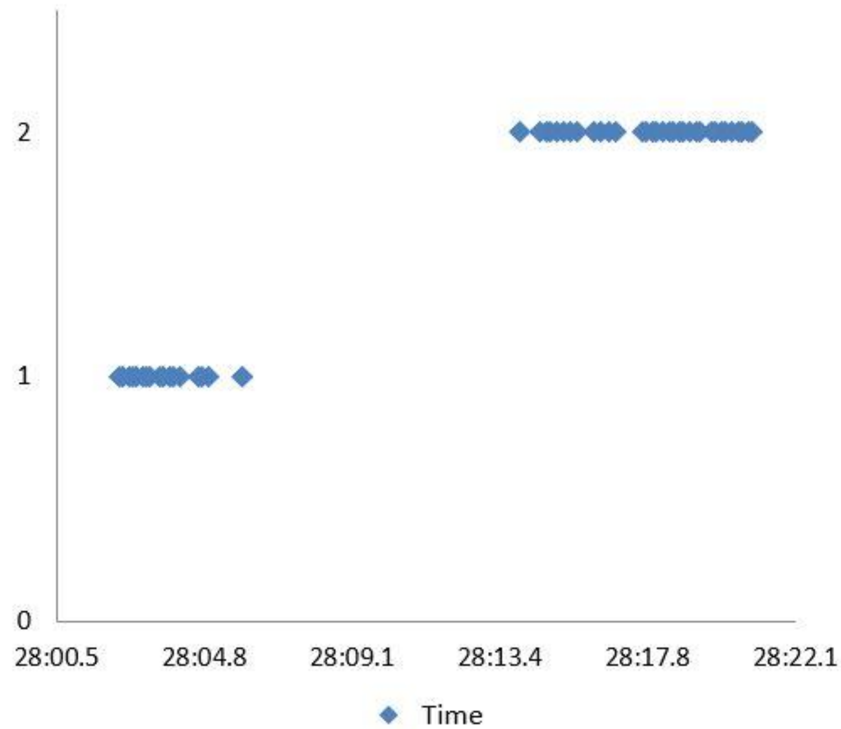


Figure 6.8 RFID Data for Walking Path 2

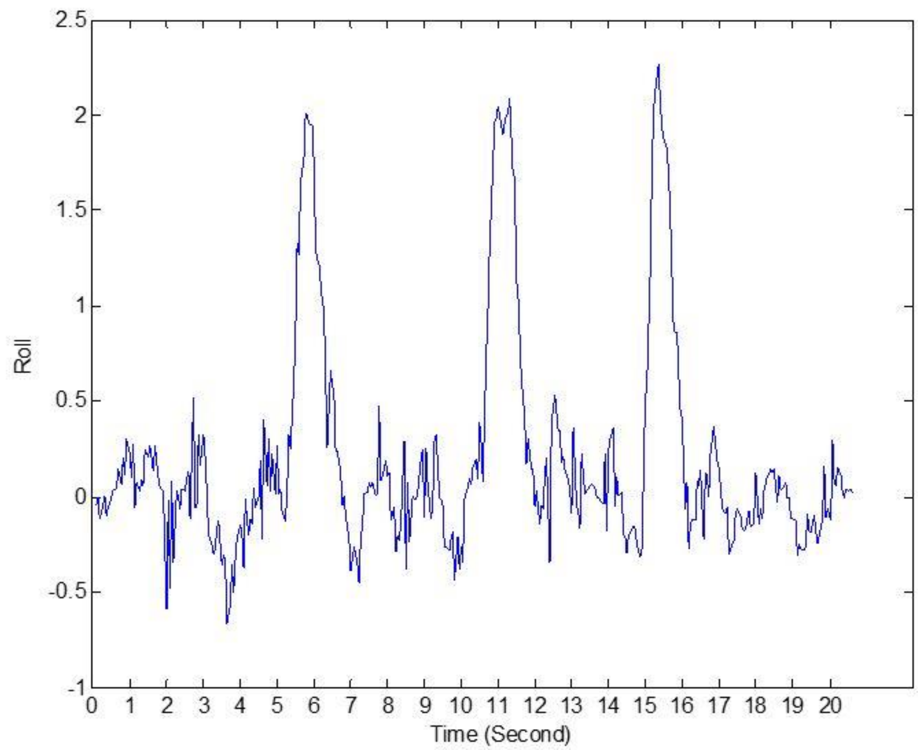


Figure 6.9 Gyroscope Data for Walking Path 2

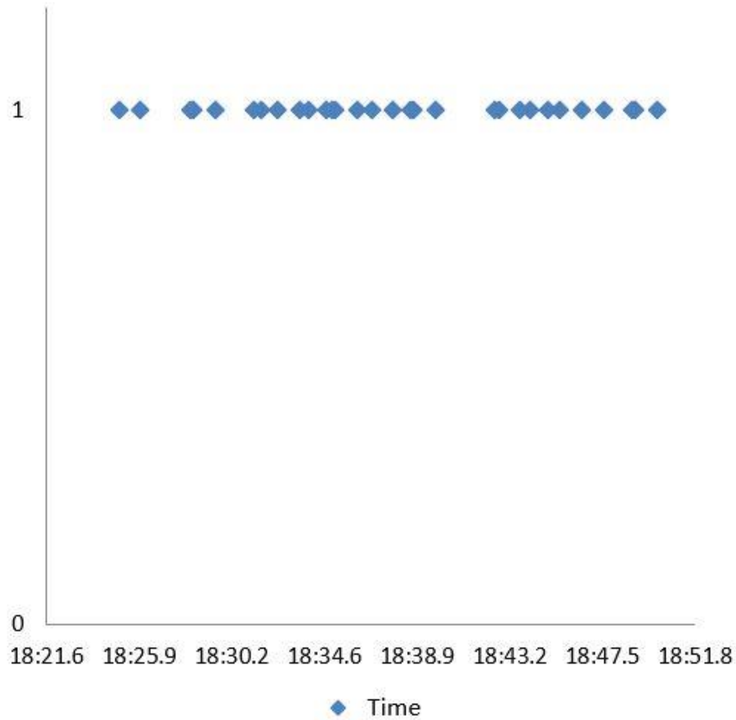


Figure 6.10 RFID Data for Walking Path 3

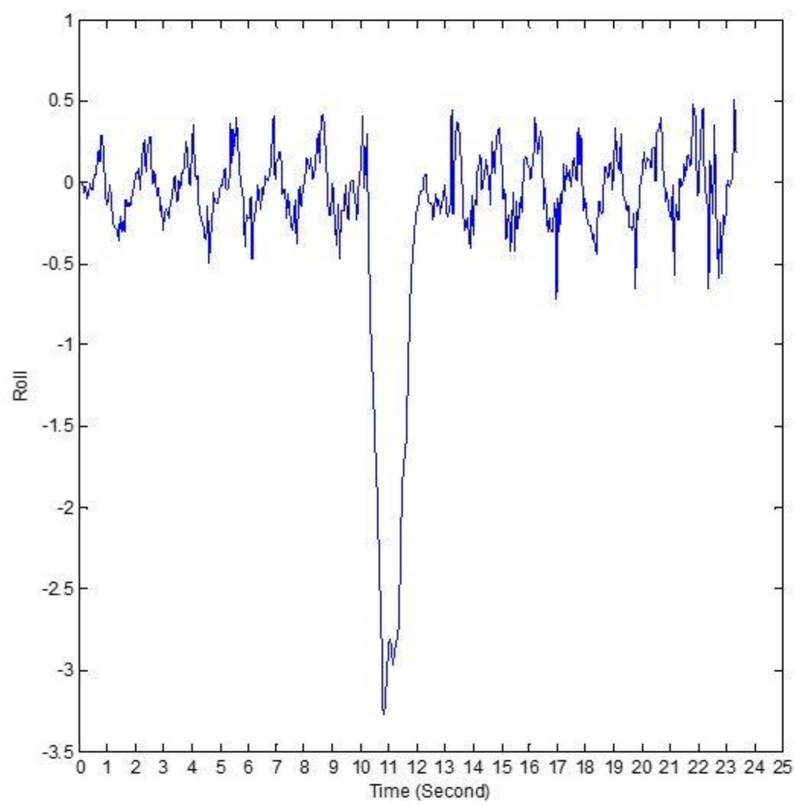


Figure 6.11 Gyroscope Data for Walking Path 3

Chapter 7

System Simulation

In order to gain a deeper insight into the whole system and the effects of possible improvements made to the system, a time and cost effective way is to simulate the RFID system using simulation modeling technology. Popular simulation technologies include Discrete Event Simulation (DES), System Dynamics (SD) and Agent Based Simulation (ABM). More details about the differences among the three different simulation modeling techniques can be found in (Maidstone, 2012, Borshchev, 2013, Borshchev & Filippov, 2004).

The ABM technique was used in this project. ABM models a system from individual level rather than from a global level which means an agent based system is formed by collective actions of every individual object. That is why ABM is also called bottom-up modeling. In an ED, there are lots of different roles, such as patient, doctor, nurse and medical equipment, facilities and so on. With an ABM, an ED can be modeled closer to the reality because all these objects have individual behavior or characteristics.

7.1 ABM System Implementation

The model is built by the simulation package AnyLogic 6.8.1 University Edition on Windows 7 platform. The package is written in Java and provides graphic interfaces for users to define and insert their own java codes for customized functions.

As the model is constructed as a tool for gaining insight into the current RFID system and possible improvements, the Minor Treatment Area (MTA) of ED where the actual RFID readers has been implemented is the only area being considered. Therefore, some of the ED process, such as Registration, Triage and so on will not be modeled in our work. The basic treatment process in the model includes waiting, treating and discharging.

Agent in ABM is an autonomous entity in the model which follows pre-defined rules to achieve some objectives while interacting with other agents and the whole environment (Laskowski et al., 2010). Agent could be almost any objects in the model including people, equipment and rooms. However, the objects with certain degree of dynamics and changes of states are those normally being modeled as agents. The agent based model consists of three types of agents, which are doctor, patient and equipment. Each agent type has a state chart which defines the states of the agent. The state charts for each type of agent are shown in Figure 33 - 35. Rules are pre-defined within each state. An agent will follow the pre-defined rules when it comes to this state.

A general process of the model runs in this way: All the doctors are waiting at the staff room at first until first patient comes. Each patient comes into the MTA with properties such as triage score. And each patient will first go to the waiting room of MTA waiting for his turn. If there is at least one doctor available, the system then associates the doctor with the patient. The doctor then tries to find an available treatment room for the patient and once the treatment room is found, the doctor will inform the patient to go to the corresponding room. The doctor associated with the patient will then go to the same room to diagnose the patient. By checking the triage score of the patient, the doctor has a low or high probability to look for a medical equipment to assist the treatment. If a doctor does need to find equipment such as a syringe in this model, he will use the RFID system to check the location of any syringe near him. Once the treatment is finished, the patient will be discharged and the relationship of the doctor and patient will be removed. The doctor can either go back to staff room to wait if there is no more patient or be associated with the next patient and follow the same process. The main interface of the ABM model is shown in Figure 7.1.

Currently, the RFID readers are placed in fixed locations in the model which simulated the current real situation of readers' placement. The model also enables the flexibility of placing readers throughout the layout of ED.

The model allows for various configurations including the number of doctors, the number of equipment and reader range. The detail information about the model configuration is shown in Table 7.1. Two options for each configuration can be switched just for illustrating the effectiveness of the functions. More options according to the real situation can be added for better results.

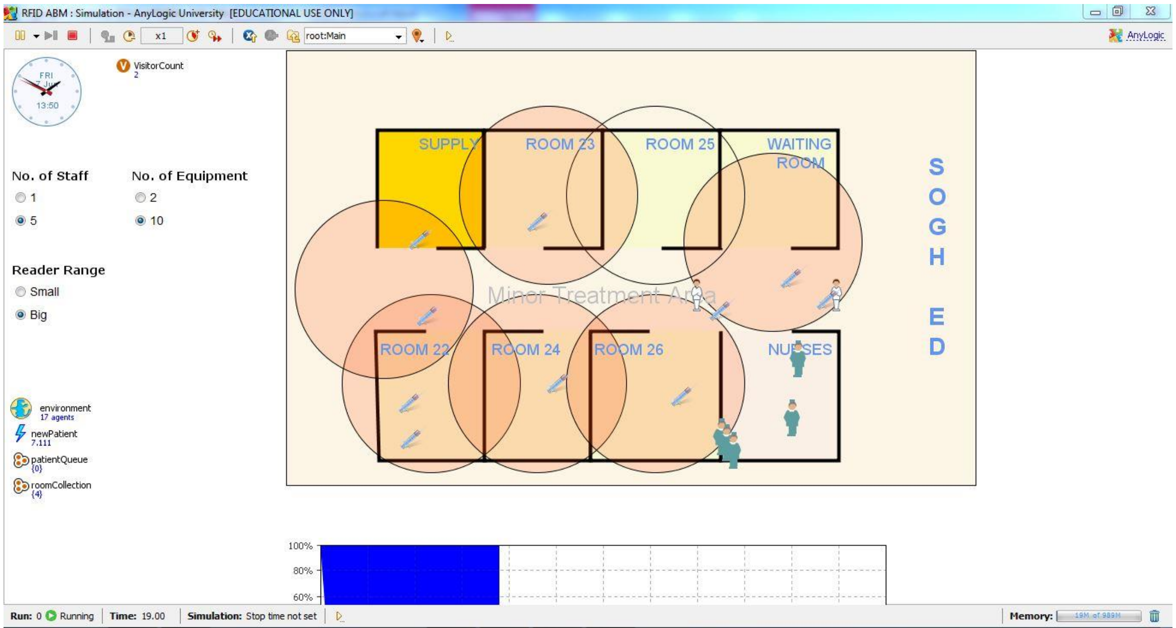


Figure 7.1 Main Interface of the ABM Model

Table 7.1 Model Configuration Details

Configurable Item	**Levels**
The Number of Doctors	1, 5
The Number of Equipment	2, 10
Reader Range	Small (5 m), Big (10 m)

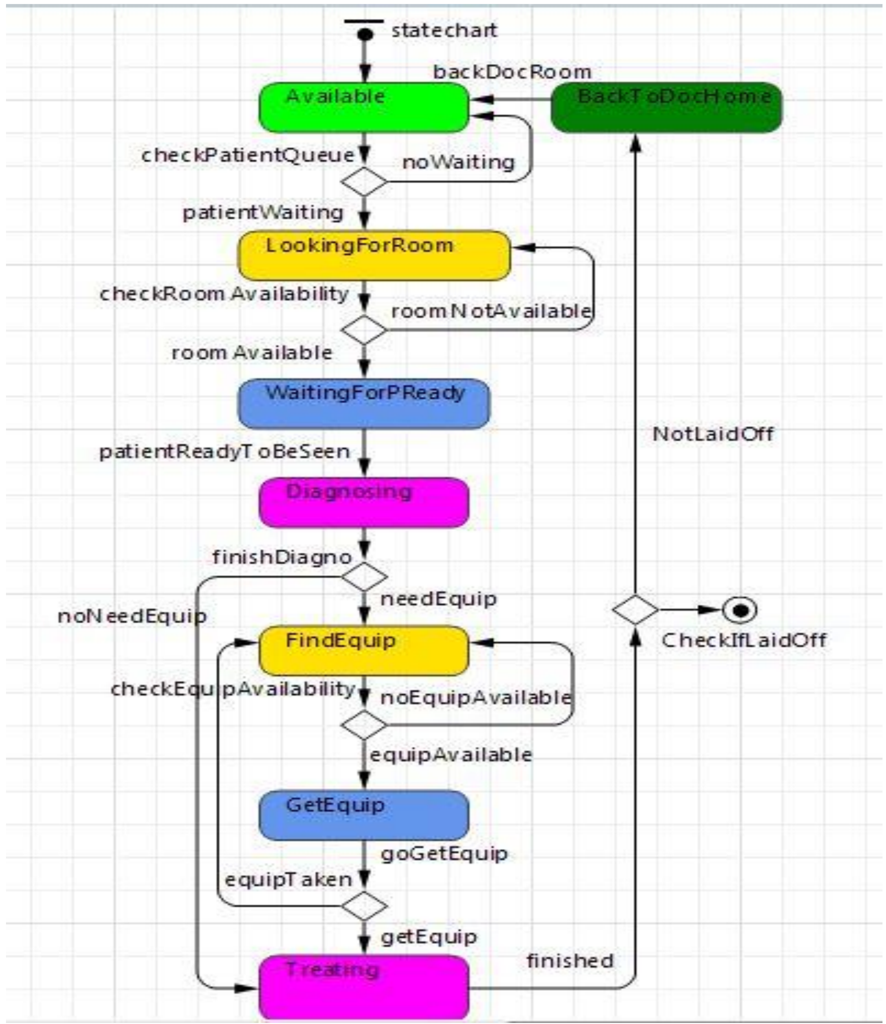


Figure 7.2 State Chart for Agent Doctor

The statistics part of the system includes the time spending statistics on important states of both Doctor and Patient, such as waiting time, treating time and so on. A Time Stack Chart with a vertial scale of 100% was used to let the user have a visualized view on the time spending in different states and find possible problem and improvement on the work process.

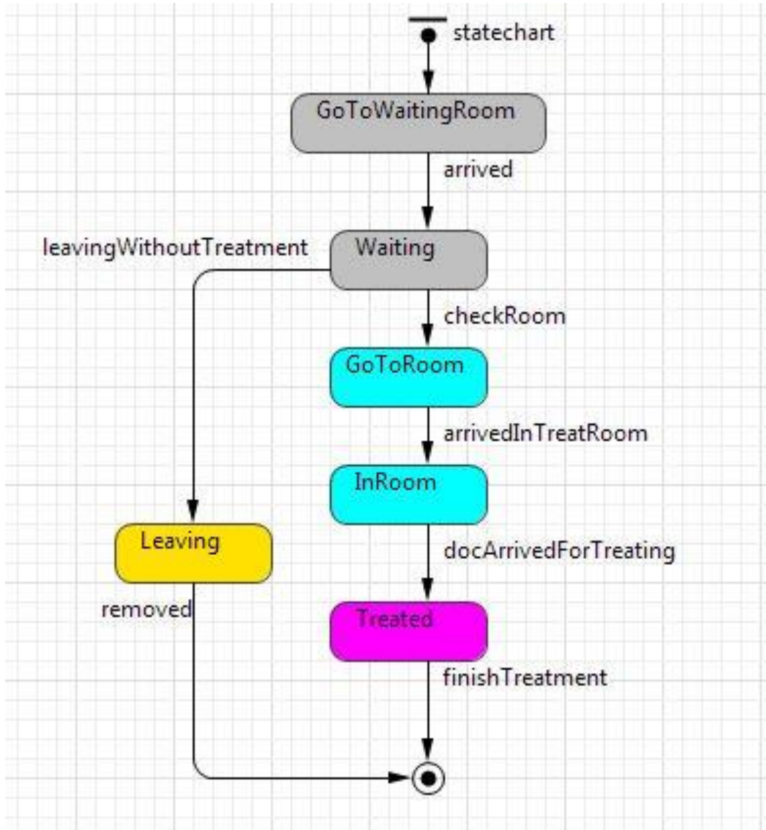


Figure 7.3 State Chart for Agent Patient

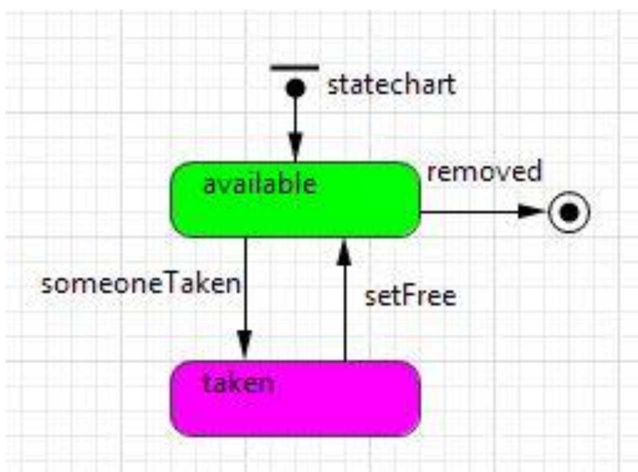


Figure 7.4 State Chart for Agent Equipment

7.2 Rules and Interaction

As agents are controlled by a set of pre-defined rules and different types of agents use different sets of rules, we will introduce the sample rules used for agents in this section. Also, the interaction of agents has also been defined with the rules.

A. Reader

The read range for a simulated RFID reader resembles a circular region in two-dimensional space. All the readers were set to scan RFID tags every second. The read range according to the model configuration mentioned in Table 7.1 can be adjusted between two levels by changing the radius of the circle. The read range of 5 m is actually represented by a circular region of 52 pixels radius in the simulation model and 10 m is represented by a circular region of 104 pixels radius. The reader ranges of two or more readers may overlap depending on the configuration. The read range may also cover areas other than the reader's intended responsible area if the range is set to 10 m level.

B. Reader/Object Interaction

Yan et al. (2012) proposed a read detection mathematical model to study the relationship of read rate and the distance from tag to reader. The relationship is being utilized in the agent based model to simulate the reader/object interaction. The mathematical equation which describes the relationship in the model is shown in Equation 1.

$$p_i = \frac{1}{1 + e^{3.64 l_i - 7.86}} \qquad (1)$$

where p_i represents the tag read rate at reader i, and l_i represents the distance from tag at location (x, y) to reader i at location (x_r, y_r), and is given by:

$$l_i = \sqrt{(x - x_r)^2 + (y - y_r)^2} \qquad (2)$$

From Equation (1), we can see that the overall tendency of read rate and distance is that the farther the distance is, the lower the read rate is.

A reader reads a tag with the read rate calculated by Equation (1) every time it scans tags. In other words, a tag would not be read every single time when it comes into the read range of a reader. The probability of being read depends on the read rate calculated at the time of reader scanning. This managed to closely simulate the readers scanning in the real world.

The tag collision is not considered in this simulation as the number of tags used in the real system is much smaller than the number of tags that a reader could handle simultaneously. Also, any tag collision case can be assumed to be solved within a time period considerably shorter than the tags traversing the reader.

C. Doctor

A doctor would usually follow the conventional working flow as modelled in the state chart of agent doctor in Figure 7.2. However, in order to make the model closer to the real situation, more situations during a doctor's daily work process should also be considered, which enable a doctor act in different ways rather than follow the straight line in the state chart to the end. There are six branches currently being modelled for transitions between states as shown in Table 7.2.

Table 7.2 Branches between States

States Involved	Branch	
	True	**Default**
Available, LookingForRoom	There is at least one patient waiting	No Patient Waiting
LookingForRoom, WaitingForPReady	There is at least one treatment room available	No Treatment Room Available
Diagnosing, FindEquip	If the triage score of a patient is greater than 2	If the triage score of a patient is smaller than 3
FindEquip, GetEquip	There is at least one equipment available	No Equipment Available
GetEquip, Treating	Successfully get equipment	If the equipment is taken by others
Treating, BackToDocHome	If the doctor was informed being laid off	The doctor was not laid off

With considering more possible situations of doctors' behaviors, each doctor in the model may behave in different way. For instance, some of the doctors may find a treatment room and proceed to the diagnosing state, while others may find no treatment room is available and have to keep waiting and checking the room availability. This would affect the whole treatment process and time for doctors, and some emergent situations would possibly appear which is beyond the modeller's expectation. This is the meaningful for an agent based model.

D. Patient

Similar to agent doctor, agent patient also usually follows the straight line in the state chart as shown in Figure 7.3 down to the end but there are also some branches for modeling different actions. For example, a patient may leave without being treated after checking the waiting queue. If the number of people waiting excessed the patient's tolerance, then the patient has a possibility to leave without being treated. Otherwise, the patient will never leave until his turn.

In this model, a leaving rate will be generated in uniform distribution if more than 10 people are waiting ahead of a newcomer. The rate represents that the patient has the possibility of leaving without being treated by the rate, however the patient will never leave if there are less than 10 people waiting ahead of him at the time of checking.

E. Doctor/Patient Interaction

There are several rules used to illustrate how doctor and patient interaction is modelled. The rules of Doctor/Patient interaction are shown as below.

- A doctor may check the patient waiting queue to get the first patient in the queue into treatment when he is available for treatment.
- A doctor may find an available treatment room for the patient and inform the patient to go to the designated treatment room by sending messages to patient.
- A patient may send a message to a doctor when he arrive the treatment room and be ready to be treated.
- A doctor can check the triage score of the patient and decide if he will need the medical equipment according the score. If the score is above 3 in a scale of 6, the doctor will go to find a medical equipment which means the patient's condition is relatively severe which needs the assistance of the medical equipment.
- When finishing the treatment, a doctor will tell the patient that he could leave by sending the message to the patient.

7.3 Result and Analysis

The mean time spending in each state for a doctor or a patient was calculated and reflected on the time stack chart as shown in Figure 7.5. The time stack chart above is for agent doctor and the chart below is for patient. The effect of different system configurations such as different number of doctors and different number of medical equipment can be observed on the time stack charts as the configurations change.

In summary, this part of research built a RFID-enabled MTA model with several basic adjustable variables as an attempt to implement more improvement methods for tracking accuracy. However, the difficulty point is at modeling RFID readers and radio propagation (Floerkemeier & Sarma, 2009). The model can be closer to the real environment if the reader's uncertainty can be simulated in a better way. The model can still be a tool to investigate the improvement in patient flow by using RFID.

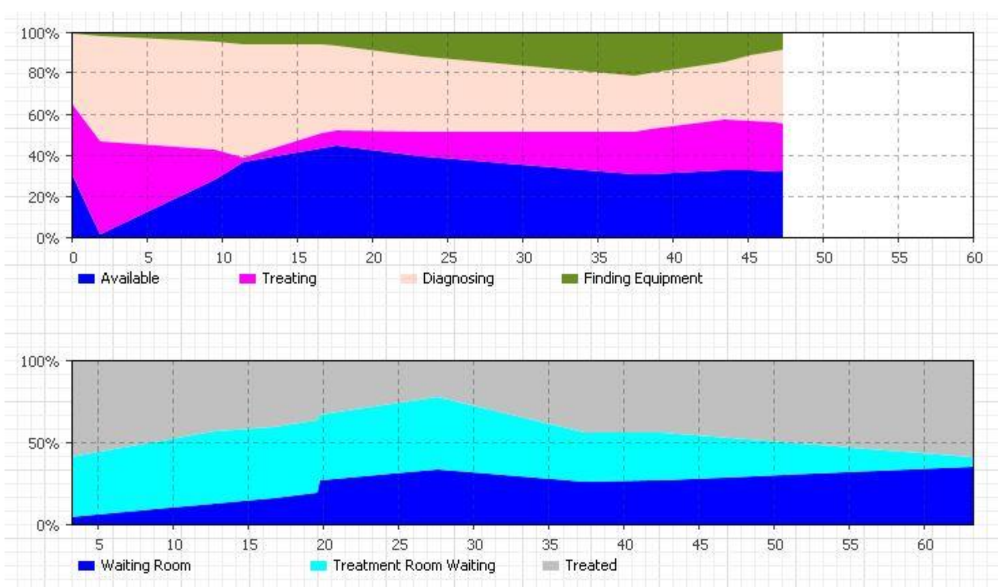


Figure 7.5 Time Stack Chart for Agent Doctor and Patient

Chapter 8

Conclusions and Future Work

8.1 Conclusions

A RFID system for personnel tracking in healthcare has been studied from different perspectives with the purpose of improving its tracking accuracy. The system tracking accuracy has been firstly improved from the perspective of data cleaning algorithm. With a read-rate based data cleaning algorithm implemented in the RFID middleware, the RFID reading data has been filtered. The proposed algorithm improved the traditional mechanism by outputting the final data filtering result at the end of a window rather than at the time when the count of a reading reaches the threshold. The reason is to allow the actual correct readings more time to be read and overtake the count of false readings in case of the count of false reading is higher at the very first moment due to the unstable radio signal. This improvement may help further improve the accuracy. The algorithm has demonstrated its ability to improve the accuracy of the current system.

However, it has been found that the data cleaning algorithm might perform unexpectedly if the RFID system was not optimally configured. In this case, an optimization method was suggested for best configuring factors that have significant influence on the system performance. The effects of read ranges of multiple readers have been studied in experiments using a full factorial design. The results gave out a combination of read range values that all readers deployed in the ED should set to for achieving best reading accuracy. The healthcare decision makers and RFID implementers could refer to this method when they are planning to implement or have already implemented but want to optimize a RFID system for patient or asset tracking.

With the intention of studying the RFID system in a cost and time effective way, a RFID-enabled ED has been modelled by agent-based modeling technique. The basic ABM framework for the RFID-enabled ED consist of three agent types, states for each agent type, basic ED environment and interactions between agents. The model can also be run in different configurations. More complexities and configurations can be easily added in the future based on the current framework.

8.2 Research Contributions

This research proposed several feasible approaches to improve the tracking accuracy for a RFID system which is based on the actual system implemented in the local hospital (SOGH ED). The accuracy improvement problem has been investigated from a comprehensive perspective in this research. Methods from different viewpoints including data cleaning, system optimization, sensor fusion and simulation have been proposed and tested in the actual application environment. Such broad investigations have never been conducted on a single system by other past research. Similar improvement from only single individual viewpoint such as RFID data cleaning might be proposed before, however, some of them does not fully work for this specific application and others are not for healthcare environment at all. Overall, this research contributes to a comprehensive improvement method for RFID tracking system not only for SOGH ED but also for other similar healthcare institutions. They can use these approaches as a guideline to tune their RFID systems for personnel tracking purpose.

8.3 Recommendation and Future Work

Based on the current situation of the RFID system in SOGH ED, data cleaning algorithm and optimization method can be implemented onto the system and achieve a best accuracy of about 87%. These methods are robust and work for almost all situation as a volunteer changed different locations in a room or an area near entrance/exit during one data collecting period to average out the possible bias in the experiment.

However, the current data cleaning algorithm is based on read rate since the readers do not provide RSSI or time related parameters for localization. Although the read rate is generally reliable based on the experiment results, it still shows some unsteadiness under heavily overlapped reader coverage especially near the border. One recommendation for future upgrade is that lower frequency readers (for example, 902-928 MHz UHF Antennas) with RSSI or time of arrival parameters can be added in. Lower frequency readers have shorter read range of about maximum 10 meters that is much shorter than the 100 meters of current 2.45GHz readers. For the application in ED environment, UHF reader is sufficient to provide considerably big coverage area and reduce more unnecessary overlaps. Also, the RSSI or the time parameters may suggest finer distance information.

The data fusion technique has not been tested under the current ED environment, however, it is a promising direction to follow up. If a sensor can be combined with a RFID tag as a sensor tag, a person carrying the sensor tag will be tracked using two different data sources at the same time. As RFID enables coarse location information and sensor data normally enables personal movement information, the two types of information will enable more possibility for inferring the relationship between the person's location and his movement, which would help tracking. Additionally, as smart phone is becoming more and more popular, this naturally brings lots of possibility of utilizing smart phone sensor data. iBeacon, an indoor localization technology by Apple, enables personnel tracking by using smart phone (Newman, 2014). Since iBeacon uses Bluetooth Low Energy technology for localization, it may also experience some unreliable results as RFID, however, the sensors such as accelerometer and gyroscope that come with the same smart phone can be possibly combined with iBeacon to boost tracking ability. This is another recommendation for the personnel tracking in SOGH ED.

Future work of the data cleaning includes applying statistical and intelligent algorithms, such as Artificial Intelligence, Machine Learning, combined with the current RFID data cleaning algorithm to further improve the effect of data cleaning and filtering.

For the optimization of the RFID system, as only two levels of each factor have been studied in the experiment, the result could be better if more levels are taken into account and the regression model is formulated in the future. Moreover, the current improvement method is based on the fixed reader location. Changing reader location will also affect the read range and overlaps. Thus, the reader location factor is worth to be tested by DOE. Combining with the read range factor, the system is expected to achieve even better accuracy.

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