RFID BASED INDOOR LOCATION TRACKING

by

Edip Toplan

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ABSTRACT

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Radio Frequency Identification (RFID) attracts considerable attention because of its low cost and various area of applications. Location estimations based on received signal strength (RSS) in wireless technologies took the topic of localization using RFID technology into agenda. In our study, changes in the RSS values according to distance have been investigated in an indoor environment based on both passive and active tags. For the system in which active RFID tags are used, localization has been made using reference tags. An online radio map of the environment is created with the help of deployed reference tags. A nearest neighbor algorithm is applied in order to localize the tracked tag. However, unpredictable and non-uniform behavior of tags resulted in inappropriate location estimations. Passive tags, on the other hand, severely suffers from shadowing effect, creating biases towards to shadowed tags. The tag worn by the subject was undetectable because of the signal absorption by the human body. We have developed an algorithm estimating the location based on the drops in RSS value of the tags as tracked subject is passing by. We achieved a mean error of 0.25 m in a 2x2.5 m^2 indoor environment.

ÖZET

RFID TABANLI BİNA İÇİ KONUM TAKİBİ

Radyo Frekansı ile Tanımlama (RFID), son yıllarda düşük maliyeti ve kullanım alanının geniş olması nedeniyle büyük ilgi gören bir teknolojidir. Kablosuz teknolojilerde, algılanan sinyal gücü (RSS) kullanılarak yapılan konumlandırma sistemleri RFID teknolojisinin bu amaçlı kullanılabilirliğini gündeme taşıdı. Çalışmalarımızda, RFID teknolojisinde RSS değerlerinin bina içerisinde farklı konumlardaki değişimi hem aktif etiketler hem de pasif etiketler üzerindeki etkileri incelendi. Aktif etiketlerin kullanıldığı sistemde, konum tanımlama referans etiketleri kullanılarak yapıldı. Referans etikeleri sayesinde ortamın radyo haritası anlık olarak çıkartıldı. Konum tahmini en yakın komşu algoritması kullanılarak yapıldı. Fakat etiketlerin tahmin edilemez ve benzersiz davranışları nedeniyle yapılan konum tahminleri uygun olmadı. Pasif etiketlerin, gölgeleme etkisinden çok fazla etkilenmesinden ötürü, tahminler, gölgelenen etiketlerden yana sonuç verdi. İnsan vücudunun sinyalleri soğurması nedeniyle giyilen etiket farkedilemez olmaktadır. Kişinin etiketin yanından geçerken etiketin RSS değerlerinin düşmesine bağlı konum tanımlama algoritması geliştirildi. 2x2.5 m^2'lik ortamda 0.25 m hata payı ile konum tahmini yapıldı.

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LIST OF ACRONYMS/ABBREVIATIONS

AoA	Angle Of Arrival
CFS	Container Freight Service
FDMA	Frequency Division Multiple Access
HF	High Frequency
ILS	Indoor Location System
LBT	Listen Before Talk
LF	Low Frequency
LPM	Local Position Measurement
PoA	Phase Of Arrival
RF	Radio-Frequency
RFID	Radio Frequency Identification
RIM	RFID Interaction Manager
RTLS	Real Time Location System
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SAW	Surface Acoustic Wave
TDMA	Time Division Multiple Access
TDoA	Time Difference Of Arrival
ToA	Time Of Arrival
UHF	Ultra High Frequency
VIRE	Virtual Reference Elimination

1. INTRODUCTION

Real Time Location Systems (RTLS) provides information related to the localization of people and/or objects in real time. These systems utilize increasingly sophisticated electronic devices. Technologies such as GPS, camera vision, infrared, sound, Wi-Fi, Radio Frequency Identification (RFID), cellular, and many more can be used for both indoor and outdoor locating of people and objects. Each technology comes with its own advantages and disadvantages based on the requirements for line-of-sight, cost, range, and environmental performance. In this work, we have investigated the applicability of RFID system for RTLS in indoor environment.

Various RTLS models exist for a variety of applications. For example, you may want to detect objects at a check point, or to sense whether an object is present in a room or near a specific area. However, a much more interesting problem which is delved into in this thesis is posed by attempting a more precise localization. In this model the tag is read by the reader and is then localized externally by the custom software which marks its location in the frames which are captured from the point of view of the webcam.

RFID has long been used as an electronic identification and tracking system. In a supply chain model, automated inventory tracking can be achieved easily by the means of RFID technology. RFID technology has wide spectrum of applications. It has been used in automative industry as anti-theft immobilizer and as passive entry-systems in many buildings. It is known that there are some contactless payment methods [1–3] that are based on RFID technology. Unlike the other wireless communication protocols, ability to retrieve information remotely can be very crucial. Although RFID tags have limited amount of storage capacity, life cycle of a tag can be tracked in a distributed manner [4].

Localization is important in terms of frequency usage, power regulations, and location based services. It should also be available in indoor navigation, real time inventory or people tracking and library management. Current applications of RFID systems provide coarse-grained location information. This information is limited since it is acquired from the strategic locations like gates or corridors. Existence of a tag means it is in the range of a reader. So the accuracy of the localization depends on the dimension of the cell formed by the reader.

As the indoor localization of wireless devices became popular, localization with RFID devices began to emerge. In RADAR system [5], application of Received Signal Strength Indicator (RSSI) fingerprinting has been shown in local-area wireless networks. Especially, in context aware systems, localization in an indoor environment plays a crucial role. In healthcare applications, indoor localization can be used for assisting people with cognitive disabilities or identifying the locations of people when an alarm situation has occurred like epilepsy seizure [6]. RSSI is already available without any additional cost. RFID systems have common properties of a wireless device. Some of the already existing algorithms on wireless devices should also be applicable to RFID systems. However, there are three main problems that the indoor location systems (ILSs) have to overcome: signal reflection off the obstacles, multipath contributions in the radio-frequency (RF) location system sensors and signal attenuation when passing through the obstacles placed between the RF sources and the sensors [7]. The indoor layout structure and moving objects can cause reflection, refraction, diffraction, dead-spots, and absorption of radio signals. Therefore severe multipath fading occurs and affects the accuracy of the location sensing. In addition, RSSI values can easily be affected from environmental factors like temperature, orientation of antenna or tag, height from the ground and even from the time of day [8, 9].

There are different kinds of RFID based indoor localization systems that embed a reader or antenna (or both) to the tracked subject. Our aim is to use a localization system in a smart home environment. Monitoring human activities inside their homes and detecting abnormal behaviors. Our system is planned to address activities of elderly people, so we do not have the luxury to make them carry heavy readers and antennas. As a result of that, our system is designed to use wearable RFID tags and fixed readers with fixed antennas inside home environment.

We have designed an implemented two different systems. One is based on battery assisted tags (active tags). Active tags has higher detection ranges and are less prone to shadowing effect. RSSI values received from an active tag are similar when it is shadowed and not shadowed, as long as antennas are able to interrogate the tag. Based on that fact, finger printing approach is applied to estimate the position of the tracked tag. Finger printing is simply getting RSSI values of the tags at different positions in the environment and hence creating a radio map of the environment. However, items in the houses and the radio map of the environment are frequently changing. To adapt these changes, we use reference tags and get an online radio map. Then we apply K-nearest neighbor algorithm to approximate the location of the tracked tag. Because of the non-uniformity and unpredictability of the RSSI values of the tags, radio map generated fails to represent the real radio map of the environment.

The other system design is based on passive tags. These tags don't have an internal battery and communicate based on backscattering. As a result, they are severely affected from shadowing. Most of the time, tag worn by the subject becomes undetectable and hence making the usage of radio map inappropriate. Although shadowing seems to be a weakness of the system, we achieved to make location estimation by tracking shadowed tags. Shadowing is a result of subject being near by the tag. We can detect shadowed tags by looking at the drops in RSSI values of the tags in the environment. We have achieved to localize the subject with an average error of 0.25 m in a 2x2.5 m^2 environment.

2. RFID TECHNOLOGY

RFID systems are an automated identification, and data collection technology with a wide array of applications. The requirements from one application to another vary extensively. Generally greater operating frequency and power will result in greater transmission range between the tag and the reader. Some applications require short range, i.e. one centimeter at the low operating frequency of 13.56 MHz, while other applications, particularly those with extended range requirements, will necessitate the use of UHF. The RFID network is composed of three parts: RFID tags, RFID readers and information system.

2.1. RFID Tags

The tag identifies the unit it is attached to, and may contain other useful data as well. Tags use the energy of the radio waves to communicate with the readers. Depending on the energy source they utilize, RFID tags are classified in three groups. Active tags have an embedded battery. Battery powers its RF communication circuitry so that the RF reader can transmit low power signals to trigger the tag. An active tag can also have built in modules like memory, sensor or cryptography. On the other hand, passive tags utilize transmission power of the reader. They have no internal battery. A typical passive RFID tag includes an antenna, and a rectifier for deriving power from an electrical field, and a control unit. An application subsystem within the tag would require additional processing capacity, and may include capabilities such as temperature, shock, or pressure sensing. Passive tags are much cheaper than active tags and smaller in size. However, they have very limited functionality. The last type of tag is a hybrid of these two. Semi-passive tags have also a battery like active tags but batteries do not power the tag continuously. Battery powers the tag only during transmission. Tag is activated when a signal is received from the readers like passive tags.

Tags are also classified according to their operating frequencies. Table 2.1 summarizes the frequency ranges and features of the tags according to this classification method.

Tags are defined by a certain protocol, which is typically programmed into the tag. Active tags used in our system operate according to a specific protocol defined by the manufacturer and EPC Class 1 Gen 2 [10] protocol is the protocol of interest in using passive tags. EPC Class 1 Gen 2 is the current protocol most often used with passive UHF tags. Technological development has been hampered by the lack of standardization, and this is no less true for UHF RFID systems. EPC is a standardization effort in order to provide the framework for the development of the RFID technology. Tags operate as coprocessors, or slaves to the reader. Most tags (passive tags especially) do not have a backend interface, since they only communicate with the reader.

2.2. RFID Readers

The reader is a gateway to the information contained on the tag. It is comprised of RF interface, a communication control system, some sort of an application subsystem, and a network. The control system contains the protocol for interacting with and identifying the tag. This protocol is defined by the same protocol as the one on the tag; for example, EPC Class 1 Gen 2 protocol.

RFID readers collect information from RFID tags through air interface. For the air interface, there are different standards designed by different commissions. Readers use antennas for monitoring. Antennas can be differentiated according their polarization. Circular-polarized antennas emit radio waves in a circular pattern. Linear polarized antennas send radio waves in a narrow beam. Electric and magnetic (EM) fields radiated by linear polarized antenna are oriented along only one direction, on the contrary for circular polarized antenna EM fields rotate by tracing a circle perpendicular to the propagation direction. A RFID tag is usually linear polarized, so with a linear polarized antenna the tag must be oriented in the same direction of the antenna. With a circular polarized antenna the tag can be oriented in any α direction

Table 2.1. RFID operating frequencies and associated characteristics.

Band	Low Frequency (LF)	High Frequency (HF)	Ultra High Frequency (UHF)	Microwave
Frequency	30-300 kHz	3-30 MHz	300 MHz-3 GHz	2-30 GHz
Typical RFID frequencies	125-134 kHz	13.56 MHz	433 MHz, 865-956 MHz, 2.45 GHz	2.45 GHz
Approximate read range	less than 0.5 meter	up to 1.5 meters	433 MHz = up to 100 m 865-956 MHz = 0.5 to 5 m	up to 10m
Typical data transfer rate	less than 1 kilobit per second (Kbit/s)	approximately 25 Kbit/s	433-956 MHz = 30 Kbit/s 2.45 GHz = 100 Kbit/s	up to 100 Kbit/s
Characteristics	Short-range, low data transfer rate, penetrates water but not metal	Higher ranges, reasonable data rate (similar to GSM phone), penetrates water but not metal	Long ranges, high data transfer rate, concurrent read of <100 items, cannot penetrate water or metals	Long range, high data transfer rate, cannot penetrate water or metal
Typical use	Animal ID, car immobilizer	Smart labels, contactless, travel cards, access & security	Animal, tracking logistics	Moving vehicle toll

with respect to the antenna, even if only half of the radiated power density will be received by the tag. For this reason, with the same conducted input power, the effective radiated power (ERP) of a circular polarized antenna is lower than the ERP of a linear polarized antenna that has the same gain.

Aside from its basic operation, an application dependent subsystem may exist on the reader, depending on the application requirement. The reader network decodes the data and sends it to the information subsystem. The reader has a backend interface linking it with the information subsystem. The reader and the information subsystem are linked to each other via some sort of a cable or wireless communication interface. The readers themselves contain one or more antennas that are used to communicate with the tags. A reader using more than one antenna cannot communicate at a time, so for readers that implement more than one antenna, antennas are cycled from one to another. This brings extra burden to reader and decreases the performance.

2.3. RFID Information System

Information system constitutes the third part of the RFID network. Information (IDs of the tags, or the result of any specific query) from the readers are gathered to perform calculations such as localization. This is where the data collected from the tags is archived. The user is provided with various important data, and alerted if there are any discrepancies or relevant events arise.

RFID systems can be categorized in two classes according to their usage: monitoring or authentication system. In monitoring systems, a tag is inseparably attached to the inventory or person. The required information is queried and dumped in interrogation zones. In authentications systems, tags correspond to the identity of the carrier. In check points, tags are used for authentication and authorization.

3. LOCALIZATION METHODS FOR INDOOR WIRELESS NETWORKS

Indoor medium, is a harsh environment for radio propagation. Radio propagation is exposed to several problems like multi path, rare line of sight (LOS), absorption, diffraction, reflection etc. As a result, the signal cannot be measured directly. There are different localization schemes in the literature and they can be categorized in three different groups: distance estimation, environment analysis and proximity.

3.1. Distance Estimation

Most of the distance estimation approaches are based on two methods: trilateration and triangulation. The trilateration method determines the position of an item using range information estimated at several separated reference points [11]. In a two dimensional geometry, when it is known that a point lies on two curves such as the boundaries of two circles then the circle centers and the two radii provide sufficient information to narrow the possible locations down to two. Additional information may narrow the possibilities down to one unique location.

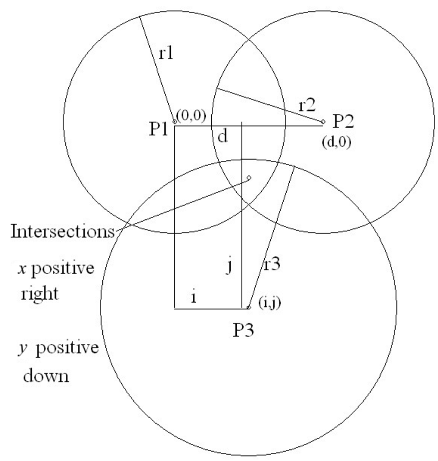


Figure 3.1. Trilateration.

Assuming that unknown object is located at point (x, y) (Figure 3.1),

$$r_1^2 = x^2 + y^2, \tag{3.1a}$$

$$r_2^2 = (x - d)^2 + y^2, \tag{3.1b}$$

$$r_3^2 = (x - i)^2 + (y - j)^2 \tag{3.1c}$$

x can be calculated by subtracting Equation 3.1b from Equation 3.1a,

$$x = \frac{r_1^2 - r_2^2 + d^2}{2d} \tag{3.2a}$$

Assuming that circles with radius r_1 and r_2 intersect on more than one point, i.e. $d - r_1 < r_2 < d + r_1$, using Equation 3.2a and 3.1c yield:

$$y = \frac{r_1^2 - r_3^2 - x^2 + (x - i)^2 + j^2}{2j}, \tag{3.3a}$$

Unlike trilateration, triangulation first defines a base line, thus defining two points of the triangle and a segment length. The next step is to carry out two angle measurements [12]. Figure 3.2 illustrates the situation. It is trivial to calculate the location of unknown point C using coordinates of known points A and B together with the known angles. Value d can be extracted by using Equation 3.4,

$$d = \ell \,/\, (\tfrac{1}{\tan\alpha} + \tfrac{1}{\tan\beta}) \tag{3.4}$$

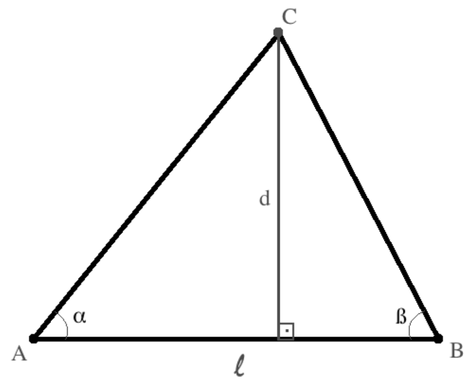


Figure 3.2. Triangulation.

Based on triangulation and trilateration some methods have been developed in order to make localization in wireless channels.

3.1.1. Received Signal Strength (RSS) [13, 14]

The attenuation emitted signal strength is a function of distance between tag and antenna. Loss in strength occurs due to propagation. There are several models to represent the propagation loss. However, in indoor systems, these methods should be adapted according to the environment because of the effect of multi path and shadowing changes.

3.1.2. Time of Arrival (ToA) [15, 16]

Distance is measured according to propagation time of the signal. Time synchronization between two nodes (transmitting node and receiving node) must be done precisely. The distance from the transmitting node to the receiving node is then determined by multiplying this propagation delay by the propagation speed, which is the speed at which the signal travels or disperses in space. There are several techniques that utilize ToA. These techniques require high resolution synchronized clocks imbedded on transmitting and/or receiving nodes [17]. In one such technique, the system finds the difference in the propagation delays recorded by several transmitting nodes, and uses this difference to estimate the distance between the receiving node and the location sensors. It is required that the measurements from all the transmitting nodes be precisely synchronized in time in order for this technique to work.

In another technique, the signal transmitted by the transmitter would contain the data regarding the exact time of departure of the signal. The receiver would then know the flight time of the signal and calculate its distance from the transmitter based on the estimated propagation speed. Some techniques eliminate the requirements for a high resolution clock embedded on the receiver. This is achieved by using the total time it takes for the signal to be transmitted, and for the reply to be sent back by the tag.

ToA techniques are difficult to apply since electromagnetic propagation speeds are at the speed of light, making the measuring of the propagation delay very difficult especially at close ranges. ToA techniques cannot be applied to our RFID systems. This is because the protocols, that our readers operate, implement an anti-collision algorithm which utilizes randomized time slot procedure. So the time it would take for a particular tag to respond to a reader quarry, will vary depending on the time slot allotted for that particular tag.

3.1.3. Time Difference of Arrival (TDoA) [18]

Time difference between transmitting and receiving node is measured at multiple measuring units. This method can be considered as the revised version of ToA, in which precision time synchronization is unnecessary. Two kinds of transceiver, such as ultrasound and RF, are installed at the nodes. The transmitter sends out RF and ultrasound beacon signal simultaneously, then the receiver receives them in different time. Combined with the transmission speed of ultrasound and RF signal, the range between transmitter and receiver is computed. Though this gives fairly accurate results, it requires additional hardware at the sensor nodes to receive the ultrasound signal, which increases the energy dissipation and complexity of node. Like ToA method, this method is also not applicable to our RFID systems because of the limitations in the operating protocol.

3.1.4. Phase Of Arrival (PoA) [19]

This method uses the delay, expressed as a fraction of the signal's wavelength, to estimate the distance. The drawback of this method is that it strongly requires LOS to limit errors.

3.1.5. Angle Of Arrival (AoA) [20]

This positioning technique is based on triangulation. The angle is implicitly obtained using the angular rotation of the receiving antenna. Recorded angle is the one that maximizes the received signal strength. The application of this method suffers from shadowing and multipath reflections. As a requirement of our system, we have fixed antennas, as a result we cannot apply this method to make localization.

3.2. Environment Analysis

In environment analysis, information on the environment is gathered. After gathering, the location of the tag is determined by matching the appropriate location from the set of location information. Information about the environment is called fingerprints. In most cases, fingerprints are RSSI values. K Nearest Neighbors (kNN) and a radio map algorithm can be used to localize a targeted tag. kNN can be used to generate a radio map database. Applying kNN to known location information before storing it in the database can increase the accuracy during the lookup phase. During real time readings, k closest matchings to the reading can be used to determine the location of the tag. The error is yet another parameter that can be useful in these applications. Root mean square error is a good measure for this task.

There are also probabilistic methods [21–23] to find the location of the tag. In these approaches, the tag is assumed to be in different locations with a belief value for the tag to be there. Different kinds of methodologies have been developed based on this Bayesian approach.

3.3. Proximity

Proximity measurements simply report whether or not two devices are "connected" or "in-range". However, the term "in-range" may mislead readers to believe that proximity is purely a function of geometry - whether or not two devices are separated by less than a particular distance. In fact, proximity is determined by whether or not a receiver can demodulate and decode a packet sent by a transmitter. Given the received signal and noise powers, the successful reception of a packet is a random variable. The proximity carries considerable information regarding sensor location m a binary variable. The proximity based localization has been used by numerous researchers for localization in ad hoc and wireless sensor networks [24].

4. RFID LOCALIZATION TECHNIQUES

Generally, RFID is being used for its identification property. A case study by Ochiai [25] describes how RFID implanted surgical instruments inside the hospital can be tracked. Medication of patients have been tracked via RFID tags embedded into wristlets for a very long time [26, 27]. IBM and Japans Kureha Environmental Engineering are tracking medical waste containers equipped with RFID tags [28]. In their survey, Alemdar and Ersoy [6], give detailed information about the usage of RFID technology on localization of cognitively impaired patients. They also mention system design considerations. Most of these studies utilize the proximity property as a location indicator [29, 30]. Locations are estimated in terms of control points. RFID reader antennas are positioned in critical points in order to create fields of detection.

In 2009, IBM developed a container tracking system for Ringnes AS through its partner Intermec [31]. The aim was to get an overview of the freight flow at production facilities of Ringnes AS. The company wanted to optimize the flow by gaining better control of the location and status of containers on trailers at any given time. They had implemented a system for recording container location and status, based on RFID technology. Installed system provides information on how many and which trucks are outside the terminal, how many and which trucks are inside the terminal and their load status (full, empty or being loaded, and at what loading port). Ringnes installed two RFID tags on its containers, one at the back, and one on the side. Signals of the tags are captured by antennas placed at the main gate for registering arrival and departure from the facility, and at each of the 40 load gates for recording loading and unloading.

In the construction field, it is important to know the amount and the current location of the materials on the way to the construction area for scheduling the next delivery. RFID is a beneficial technology as it relates to the materials receiving process [32]. Song *et al.* [33] have developed a proximity based localization system for construction material in sites. A person having GPS and RFID modules embedded devices travels on the construction site, RFID tag attached materials are positioned relative to the person whose location is known from GPS receiver.

Malmberget mine in Sweden installed a mining safety system in 2003 to improve the safety of their workers. The system makes use of several access points installed at strategic locations in the mine. All workers are equipped with UHF active RFID tags, which are recognized and registered when they are within the reading range of the access points. The system stores and displays the number and the last location of personnel, so that the rescue team can quickly locate them under emergency [34].

Existing techniques for localization are adapted from other wireless technologies for indoor localization with RFID. Unlike sensor or ad-hoc networks, we have very limited functionality in RFID tags so localization must be centralized. Mostly, the proximity approach is applied when passive tags are used. Techniques that exist in the literature are developed before can be categorized into three sections: lateration with distance estimation, environment analysis with deployment of extra reference tags, and constraint-based approaches.

4.1. Distance Estimation

4.1.1. SpotON [35]

Multiple readers store the RSSI values and distance is determined according to a known function of RSSI and distance. After that, lateration is applied to localize the tag. The system works by taking measurements of the RSSI of the signals. These signals would be arriving from the tags, and the measurements would be obtained by the multiple base stations that are positioned at different locations. The base stations then measure the path length of the signals traveling from the tag to the base station in order to approximate the range of the tag from the base station. The base stations are connected to a central server which puts together the values gathered from each base station. The principal of triangulation is then applied to calculate the three dimensional location of the tag.

4.1.2. Surface Acoustic Wave Identification (SAW ID-Tags) [36]

In this article, the authors have used passive tags. Interrogation of a tag is done according to the time inverse of its impulse response. The tag transmits the corrected signal and this signal exhibits an autocorrelation peak. Response with the highest amplitude identifies the queried tag. Distance measurement is done based on ToA:

$$d_i = \frac{T_{total,i} - T_{SAW} - T_{sys} - T_{cable,i}}{c_0} \tag{4.1}$$

where T_{sys} is the time delay caused by the system, $T_{cable,i}$ is the delay in the cable between antenna and the modulator. This value is calculated during calibration phase before constructing the system. T_{SAW} is equal for all tags. After acquiring at least three distance measurements, trilateration is applied to localize the tag.

4.1.3. Local Position Measurement (LPM) [37]

The system uses active tags operating at 5.8 GHz frequency. They utilize TDoA technique. Readers are synchronized using reference tags (RTs) distributed to the field. When activation command has been sent, the measured tag (MT) responds at time t_{MT}. After that, distance of the measured tag to the reader R_i can be determined according to Equation 4.2:

$$c_0 t_{diff}(R_i) = c_0(t_{MT} - t_{RT}) + ||MT - R_i|| - ||RT - R_i|| \tag{4.2}$$

According to Equation 4.2, we can estimate the location after getting at least three distance measurements from different readers for the tag.

4.1.4. PoA [38]

In [38], Povalač and Šebesta introduces a method based on the evaluation of received signal phase change during a linear frequency modulation (LFM) chirp. The phase of signal arrival is converted to the instantaneous frequency of a FMCW beat using a delay-multiply FSK demodulator with signal level normalization. Range estimation is afterwards calculated from the averaged instantaneous frequency.

4.2. Environment Analysis

4.2.1. LANDMARC [39]

In this method, kNN method has been applied to the active tag system. Reference tags are placed at fixed locations. These reference tags are deployed uniformly in the environment. According to the readings of antennas a relation is defined between each reference tag and the tag to be located. Relation is defined as: $E_j = \sqrt{\sum_{i=1}^{n}(\theta_{j,i} - S_i)}$. $\theta_{j,i}$ is the RSS value read by reader i for the reference tag at location j. S_i is the value read by reader i for the monitored node. A weight is calculated using this relation: $w_i = \frac{1/E_i^2}{\sum_{j=1}^{k} 1/E_j^2}$. Here k is the number determined for nearest reference tags. k nearest reference tags are the ones with small E values. Based on these definitions, Equation 4.3 represents location estimation.

$$(x_e, y_e) = \sum_{i=1}^{k} w_i(x_i, y_i) \tag{4.3}$$

4.2.2. Virtual Reference Elimination (VIRE) [40]

VIRE is again based on the idea in LANDMARC. Additionally, it represents a proximity map for the environment and another weight based on this proximity map.

A proximity map is generated for each of the readers. If the difference of RSS values between reference tag and the monitored tag is greater than a threshold value, the region corresponding to that reference point is assigned to one. The map generated by putting all proximity maps of all readers gives us a weight about the location of the monitored tag.

$$w_{1i} = \frac{1}{n} \sum_{i=1}^{n} \frac{|\theta_{j,i} - S_i|}{\theta_{j,i}}, \tag{4.4}$$

where n is the number of readers. Besides this discrepancy weight there is another weight coming from the proximity map.

$$w_{2i} = \frac{p_i}{\sum_{j=1}^{n_a} p_j}, \tag{4.5}$$

where n_a is the number of total regions and p_i denotes the ratio of conjunctive possible regions to the whole area. The location of the monitored tag is calculated in the same way as in LANDMARC.

$$(x_e, y_e) = \sum_{i=1}^{n_a} w_{1i} w_{2i} (x_i, y_i) \tag{4.6}$$

4.2.3. Simplex [41]

This algorithm also uses reference tags. However, here the localization is based on power levels. Readers have K different transmission power levels. Starting from the lowest power level, power is gradually increased. On each level, both the reference tags and monitored tags are assigned to that power level if they cannot be monitored in lower power levels. Then the distance $L_{i,j}$ between reader i and tag j is estimated by averaging distances from the reader to all reference tags that are also assigned to same power level. Error function (Equation 4.7) is created and the objective is to minimize this error function.

$$\epsilon_j = \sum_{i=1}^{n} (\frac{L_{i,j} - \hat{L}_{i,j}}{L_{i,j}})^2 \tag{4.7}$$

4.2.4. Particle Filter [42]

Rao *et al.* utilize reference tags as well. However, here the antenna is attached to the moving object. Based on the RSS values, it is tried to estimate the location of the reader. Environment is divided into regions, which are determined by the reference tags. Based on estimated motion of the reader, beliefs are assigned to the regions on the environment. Distance between a region and a reference tag is used for calculating a joint probability, which is the representative of the weight of being in a location. r^{ij} defines the distance between the ith particle and jth reference tag.

$$P(x_t^i|RSSI_t^{1:m}) = a_t \prod_{i=1}^{m} (P(RSSI_t^j|r_t^{ij}))P(x^i) \tag{4.8}$$

In Equation 4.8, $P(x^i)$ is the belief assigned for being at particle x^i. m is the number of measurements. a_t is just the normalization constant. Utilizing the weight of being at particle location x^i is calculated by just taking the average (Equation 4.9).

$$\hat{x}_t = \sum_{i=1}^{N} P(x_t^i|RSSI_t^{1:m})x_t^i \tag{4.9}$$

4.2.5. Scout [43]

Like particle filter, Scout is also a probabilistic approach to localization. There are reference tags and many antennas in the field. Localization is done in three stages. In the first stage, using reference tags on the site, propagation parameters are determined. In second state, the distance between the targeted tag and the reader is estimated using probabilistic RSS model. In the last stage, the location of the tag is estimated by applying Bayesian inference. Algorithm continues in an iterative way. At each iteration, the weights are corrected until a good model is obtained.

4.3. Constraint-based approach

Constraint based approaches utilize the range of the reader to determine an upper bound and a lower bound for the location of targeted tag where range of the reader corresponding to power levels should be predetermined. The space is discretized into points in order to delimit the detection area of the reader [44]. The mean of the set of points that satisfies the maximum of constraints, corresponds to the estimated location of the tag.

Table 4.1. RFID localization schemes.

Scheme	**Algorithm**	**Reference Tag Usage**	**Tag Type**	**Space Dimention**
SpotON	RSS lateration	No	Active	3D
SAW ID-tags	ToA lateration	No	Passive	2D
LPM	TDoA weighted mean squares	No	Active	2D
PoA	PoA/AoA	No	Passive	2D
LANDMARC	kNN	Yes	Active	2D
VIRE	kNN	Yes	Active	2D
Simplex	kNN Optimization	Yes	Active	2D
Particle Filter	RSS Bayesian approach, Particle filter	Yes	Active	2D
Scout	RSS Bayesian approach	Yes	Active	2D
3D Constraints	Range-free optimization	No	Active	3D

5. EXPERIMENTS WITH DIFFERENT SYSTEM CONFIGURATIONS

We can categorize our systems into two according to the tag type used. We refer the system using active tags as “active system”. Since they utilize battery assisted tags, active systems prone to shadowing effect. Most of the methods using environment analysis requires all tags to be detectable at the time of operation. However, they are inappropriate to be used for constraint based approaches because of their long reading ranges. In order to cover all methods, we also designed a system which uses passive tags. We use term “passive system” for RFID system using passive tags.

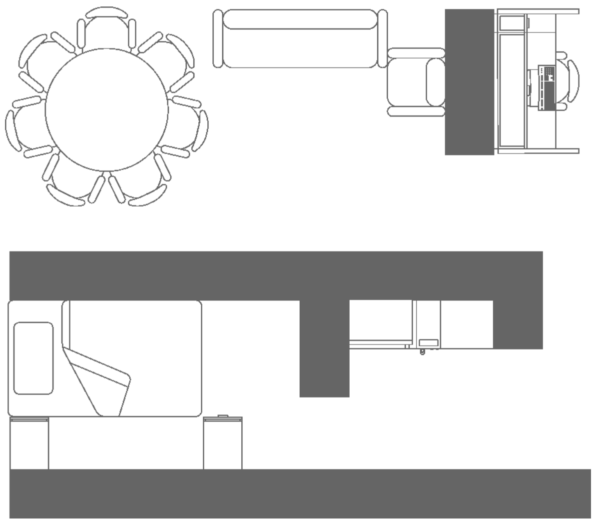


Figure 5.1. Environment.

Experiments are conducted at our laboratory in Telecommunication Research Center building in Kandilli Campus of University of Boğaziçi. Figure 5.1 is a model of the laboratory. It has a 6x5 m^2 area mainly composed of wood. A small home environment is simulated with different rooms. RF signals can propagate through the walls shown as dark gray color. Metal items are a round table having chairs with metal skeleton, microwave oven, coffee machine, our computer and RFID equipment.

5.1. Active System

5.1.1. Hardware Selection

Different measurements using different configurations have been conducted, In order to construct a model for the RSS in active system. UDEA RWID-R12 model active RFID reader is chosen for the experiments. UTAG-S11 model active RFID tag of the same manufacturer of the reader is used. Operating frequency of both the device and tag is 434MHz. It has a data transfer rate of 38.4 Kbps and communication port is RS232 (See Appendix A). A single reader has two antenna sockets so we have used two RFID readers having four antennas in total. There are limited number of RS232 ports on a computer. We need to connect each RFID reader to a computer. In order to communicate with RFID readers connected to different computers, we have implemented a network interface to receive and forward the readings from RFID reader to computer and then to network. Having both RFID readers operating at the same frequency and not having a protection algorithm like listen before talk (LBT) causes interference among readers. We have developed additional software to orchestrate these two readers remotely. This orchestrator software enabled us to make time division multiple access (TDMA) to the wireless channel thus solving the interference problem. Figure 5.2 depicts the architecture of the system.

RSSI values in our active system range from 0 to -128. RSSI measure is an indicator of RSS. RSSI values provided by our active RFID reader is unitless. In our study, unit of RSSI values is not mentioned in the active system.

5.1.2. Pre-application Stage

RSSI values from a stationary tag seems to be constant when the environment is not changing. However, as the tag starts moving, fluctuations in the RSSI values are observed. Carried out experiment is depicted in Figure 5.3. Arrow describes the motion of the observed tag.

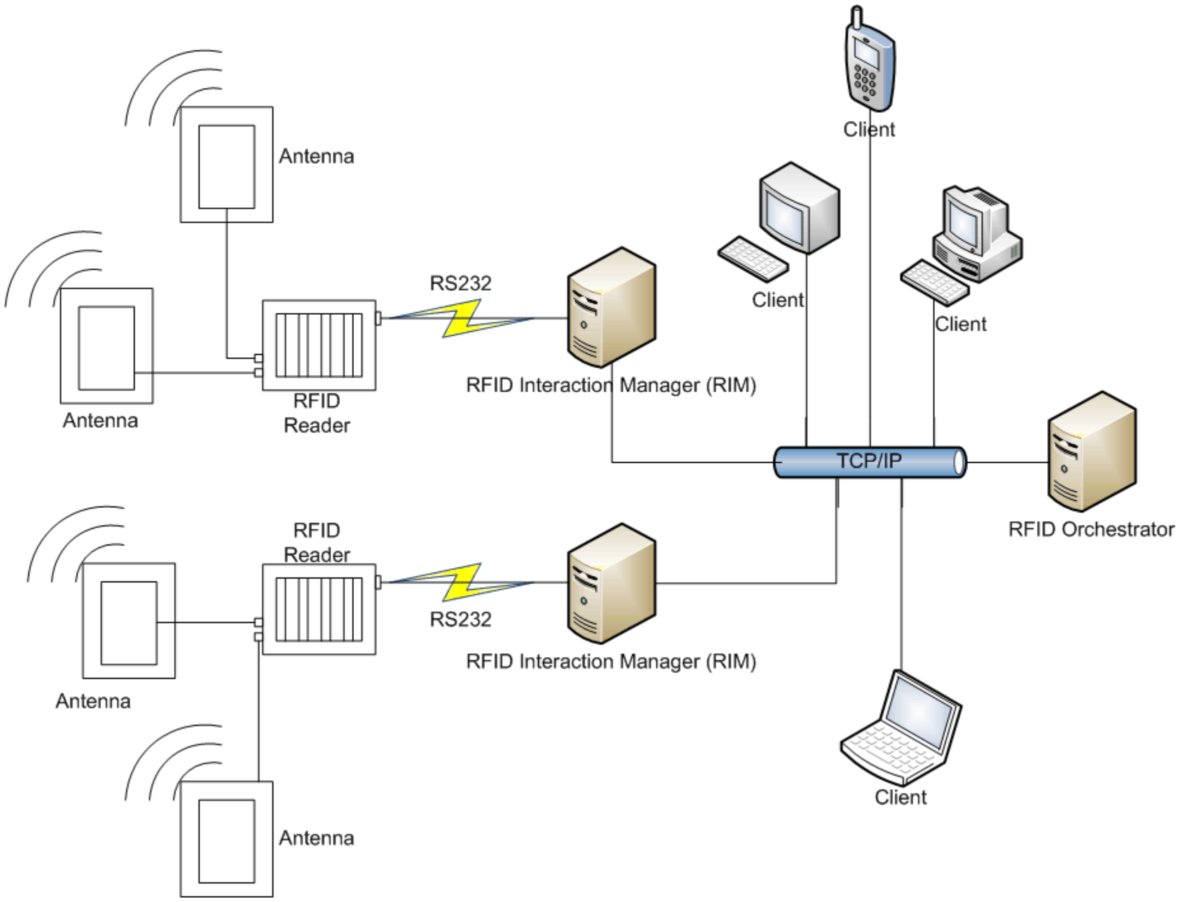


Figure 5.2. RFID Interaction Manager (RIM).

It has been shown that the received signal strength usually demonstrates a Gaussian normal distribution [45]. Based on that generalization, the mean of a sufficiently large number of independent random samples from RSSI values approximates to the real RSSI value, eliminating the effect of noise according to central limit theorem. This sufficiently large number, which we call window size (ws), is a parameter for approximating real RSSI value in our experiments. ws successive readings of RSSI are averaged. The effect of ws can be investigated from Figure 5.4. In this scenario, a tag is positioned in front of an antenna 5 m away. The tag is slowly moved towards the antenna till the distance between the two is 1.5 m. As ws increases the transitions between successive readings becomes smoother. However, the system becomes less responsive to immediate changes.

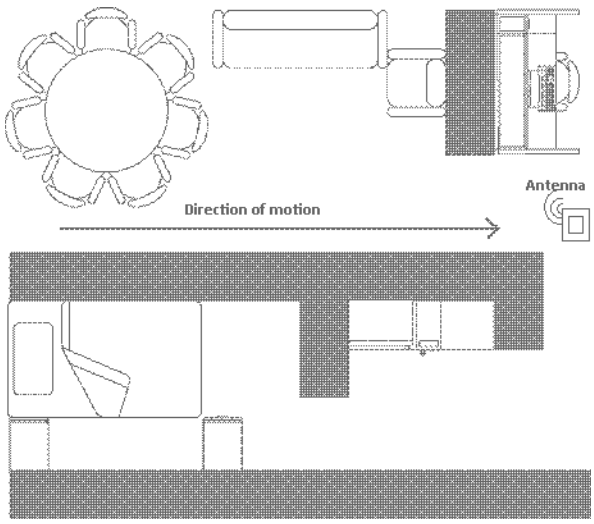


Figure 5.3. Motion for determining the effect of window size.

Assuming the pattern illustrated in Figure 5.4 represents the log-distance path loss model, we can estimate the parameters by using Equation 5.1.

$$PL(d) = PL(d_0) + 10nlog(d/d_0) \tag{5.1}$$

In Equation 5.1, d represents the distance between the transmitter (i.e., tagged object or reference tag) and receiver (i.e., reader antenna), $PL(d_0)$ is the propagation loss (in dB) measured at distance d_0; n is the path loss exponent which indicates the decreasing rate of signal strength in an environment; d_0 is a reference point chosen close to transmitter. In free space, n is two, but in an indoor environment we expect it to be greater than that value. Considering transmitting antenna power (P_t), transmitting antenna gain (G_t), and receiving antenna gain (G_r) the received signal strength (P_r in dB) at distance d can be estimated using Equation 5.2.

$$P_r(d) = P_t + G_t + G_r - PL(d_0) - 10nlog(d/d_0) \tag{5.2}$$

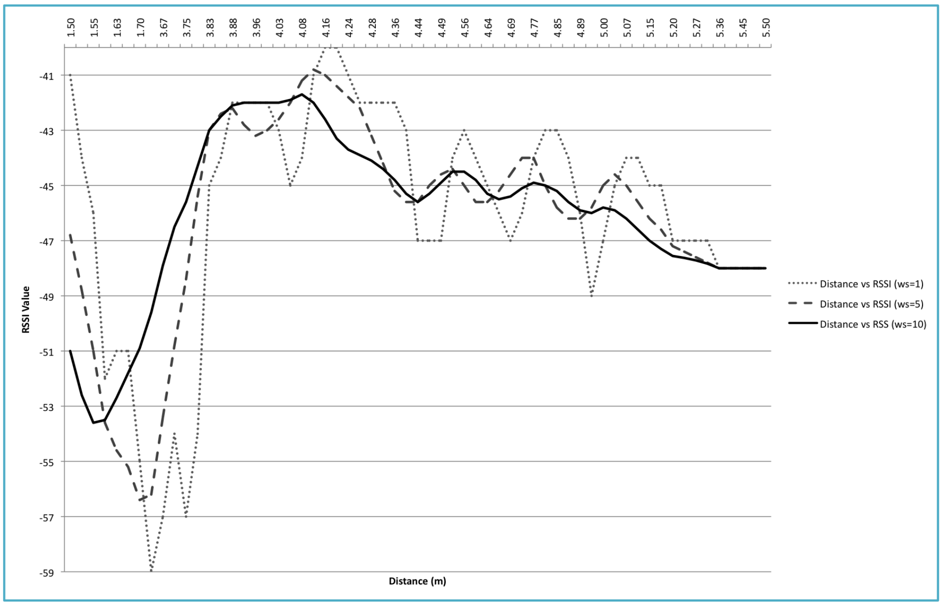


Figure 5.4. Effect of window size in motion estimation.

The sum of transmitting antenna power, transmitting antenna gain, receiving antenna gain and path loss at reference point is a constant. Equation 5.3 can be derived by calling this constant α.

$$P_r(d) = \alpha - 10nlog(d/d_0) \tag{5.3}$$

Constant α and path loss exponent n can be estimated using nonlinear fitting. Figure 5.5 depicts the regression line together with confidence interval. Fitted line resembles the data, however the experiment was conducted in LOS and at constant speed. Application of path loss model suffers from fluctuations on RSSI. These fluctuations come from the RF environment as well as the orientation of antenna and radiation pattern [46, 47]. RSSI values of a tag degrade when it is placed on a lossy dielectric object (such as human body) or a metallic surface [48, 49]. But the results are not always as expected. In the trial presented in Figure 5.7 and 5.8, RSSI readings of a tag are recorded from a single antenna. In the former trial, the tag was not attached

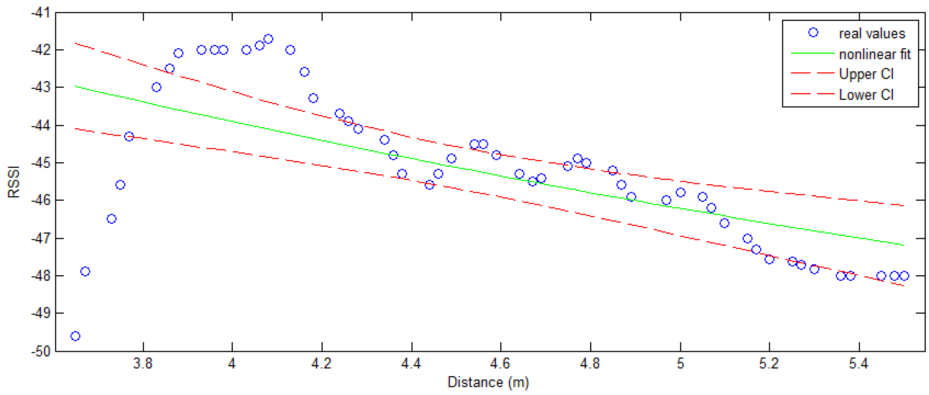


Figure 5.5. Nonlinear Fit to Distance vs RSSI readings.

Table 5.1. Average RSSI values measured when the tag is not attached to any object.

(x,y)	**1**	**2**	**3**	**4**	**5**
1	-60	-61	-60	-56	-54
2	-51	-62	-62	-62	-57
3	-54	-53	-64	-60	-58

to any object, but in the latter one, the tag was on a human (see Figure 5.6) which can be accepted as a lossy dielectric object. It is hard to get a full radio map of the environment. For this reason, we have divided the environment into grid of cell size 0.5x0.5 m^2 and got measurements over a field of 1.5x2.5 m^2 area. Closest cell to the antenna is $(1, 1)$. Darker colors represent lower RSSI values. For better representation purposes, we had converted negative values into positive ones by adding 128, since -128 is the smallest RSSI value provided by the firmware of the device. You can see the related raw data in Tables 5.1 and 5.2 respectively. Results show that even being on a lossy dielectric object does not have a significant effect on our active tags. Biggest change occurs at cell $(1, 2)$ which is 11 units. It may be because of the space between circuit and the housing of the tag.

Figure 5.9 represents the effect of the orientaion of a human when he/she is carrying the tag like represented in Figure 5.6. Samples are taken in every 45 ° rotation. The antenna measuring the RSSI values is located at the orientation of 225 °. This also

Figure 5.6. Human carrying a tag.

affects the RSSI values. It gets the highest RSSI values when the tag is oriented towards the antenna.

In the trials of our study, it has been seen that RSSI value received from a tag at a unit distance differs from antenna to antenna. The reason behind this can be that antenna locations for different trials are not exactly the same. Even changes in centimeter scale gives different results. Another reason may be the different power losses because of the cables. Depending on the fact, we considered measurements from

Table 5.2. Average RSSI values measured when the tag is on a human.

(x,y)	**1**	**2**	**3**	**4**	**5**
1	-58	-72	-61	-56	-54
2	-51	-56	-62	-58	-58
3	-58	-56	-59	-61	-53

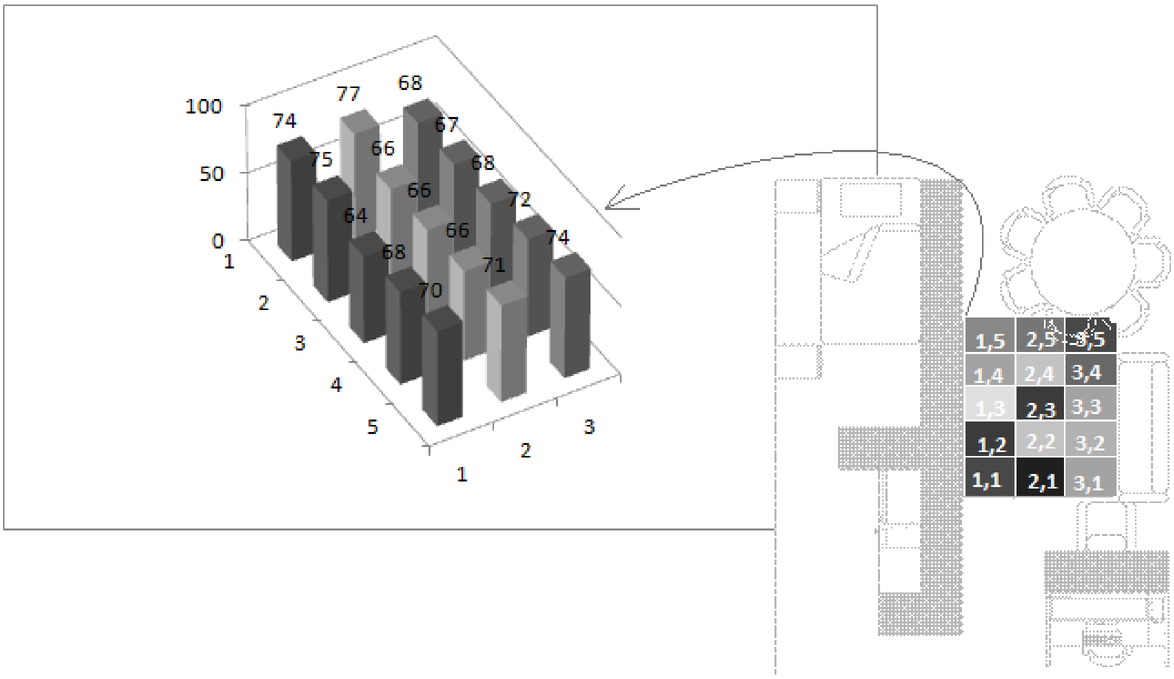


Figure 5.7. Radio map of the field when tag is not attached to an object.

each antenna independent from the others in our calculations.

Information that the RFID reader can provide is limited. Distance analysis cannot be applied because of this limitations. We were unable to apply ToA or PoA because of the limitation in the protocol of the device. Applying TDMA for inference among readers causes a big delay in the system such that the time spent on air transmission becomes in significant. AoA approach fails since we do not have an omni directional antenna. It has been shown by many researches of the field that RSS based distance estimation fails in indoor environment because of multipath, shadowing and scattering of the signals. We focus our study on environment analysis approach.

5.1.3. Application and Results

We have tested our application using two RFID reader containing total of 4 antennas. Each antenna is mounted to a vertical bar at 1.8 m height and placed to the

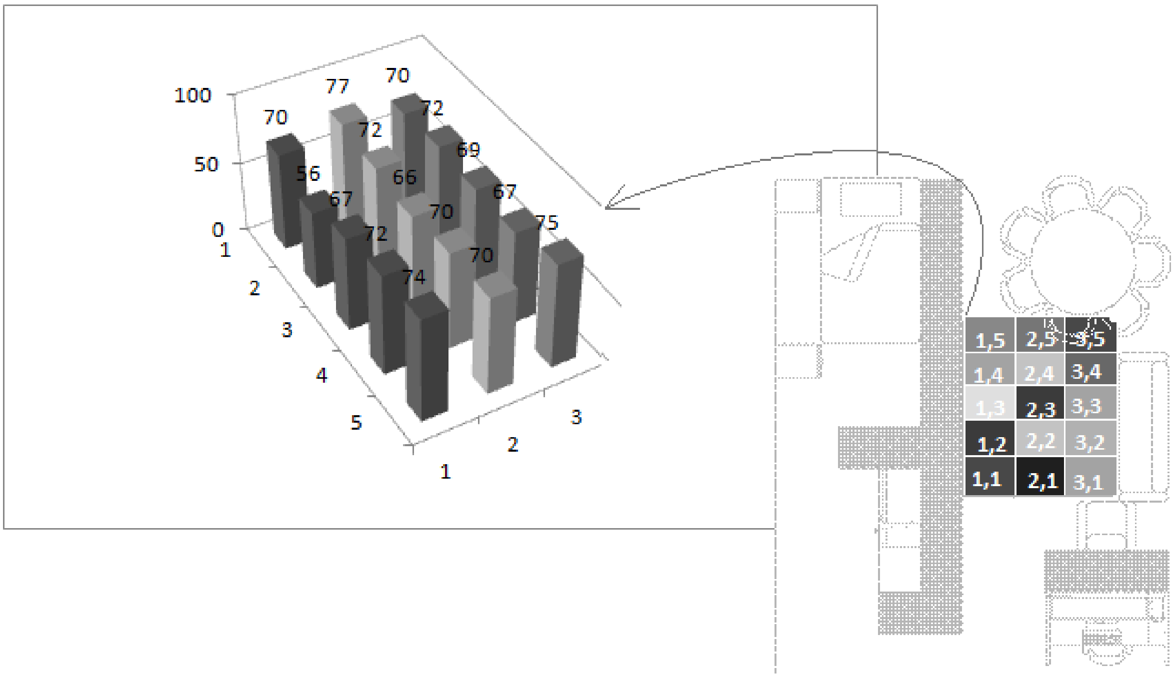


Figure 5.8. Radio map of the field when tag is on a human.

corners of our environment (Figure 5.10) facing towards the center of the environment such that maximizing the RF coverage of the area.

Using a radio map (fingerprint) for localization is a well known approach [50, 51]. It provides acceptable results [5]. However, radio map generation is a time consuming activity and indoor environments. Especially places like kitchens change continuously requiring regeneration of radio map. One can move a chair, put metal plates on to the table or redesign the decoration. It is takes too much time and effort to regenerate the radio map on frequency for each change in the environment. To overcome this problem, reference points are deployed in the environment. Reference points are composed of tags located at known positions in the environment. At each iteration the radio map is constructed using the most recent RSSI values of the reference tags. We had applied LANDMARC [39] using six reference tags and a tracked tag. Application for this purpose has a mobile interface for recording the exact position as well as calculated one. Figure 5.10 is a screenshot from user interface of the application.

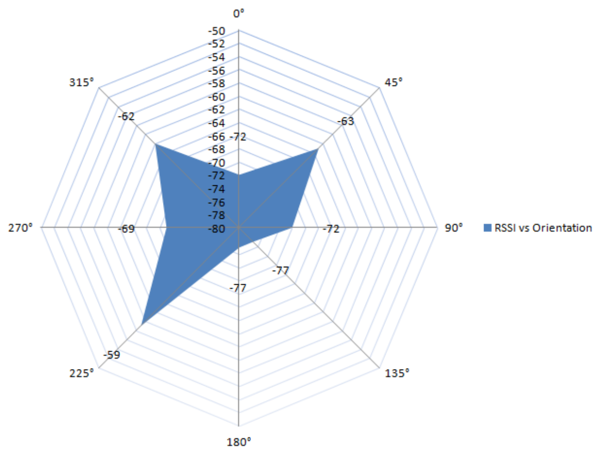


Figure 5.9. Effect of orientation on RSSI measurements.

We placed each reference tag 1 m. apart from each other. We used window size of 20, and assigned maximum power level (which is eight) to the antennas. Keeping the tracked tag on the same position by tuning number of nearest neighbors to be used we sampled different runs. We have synchronized readers in a way that at each iteration, each antenna is able to read all tags in the environment at least once. This is the main requirement of the LANDMARC.

Our experiments suggest that the number of reference tags is directly related to the distance error. Figure 5.11 shows the relation between these two. Average error is closely related to the distance between each reference tag. In our experiments, we noticed the change in meaningful RSSI values is within some interval. Unexpected values stem from instantaneous changes in the environment like (moving a chair) or shadowing by a metal or lossy dielectric obstacle. Because of this small change in RSSI values, moving inside the room has nearly no effect on the location estimation. Since the estimated location is the weighted sum of location of the selected k neighbors, estimated location is bounded with the convex hull created with these k neighbors. As a result, average estimation error is going to be approximately the half of the largest distance between two neighbors.

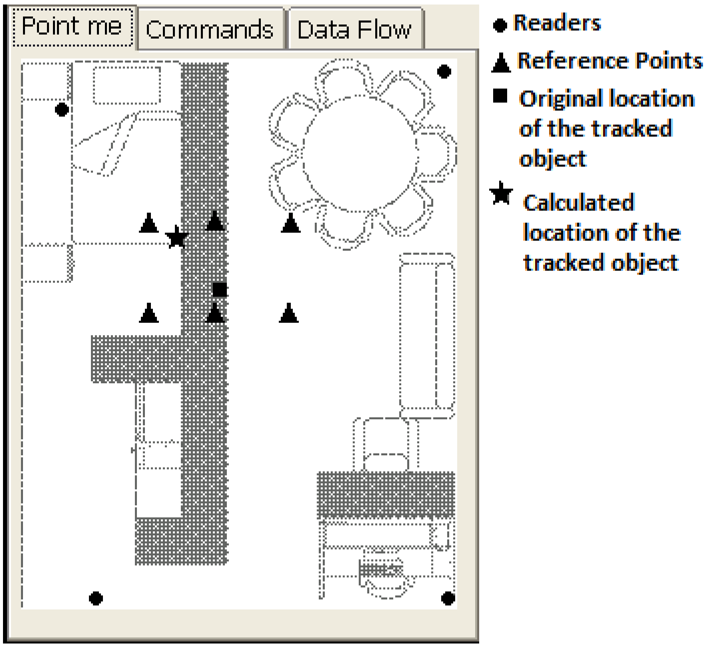


Figure 5.10. Sample run from application.

5.1.4. Discussion

Active system has a reading capacity of 2 seconds per reading of one tag from one antenna one second of which is due to the synchronization of different RFID readers. Acquired performance is too small to capture instantaneous events occurring in the environment. This number even increases when there are more than two readers working on the same environment. Using more than two RFID readers which we used

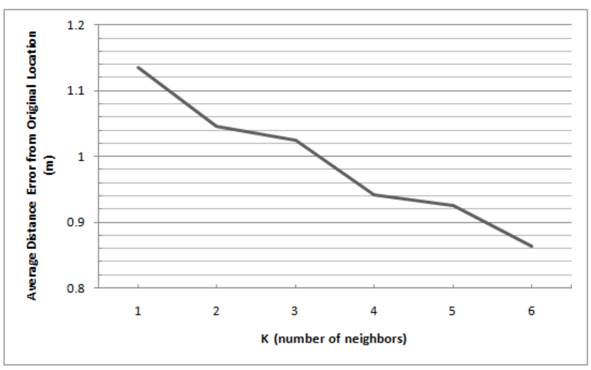


Figure 5.11. Number of nearest neighbors (K) vs Average Distance Error (m).

in our experiment is very likely to occur if we want to make localization inside the whole house. Reading range of the active readers we used was 80 m and they are likely to interfere with each other even they are placed very far end of the house. To reduce the burden of the scheduler more appropriate solutions must be provided; for example, frequency division multiple access (FDMA). We can further improve the performance by using a different RFID tag with better computation power.

The main problem with the active system is the unpredictable and independent behavior of the RFID tags. Figure 5.12 shows the situation. There are two different setups are made to detect the effect of other tags in the environment to RSSI values of the tracked tag. The tag represented similar behavior when it is alone (line with diamond dots) and when there is another tag near by (line with square dots). Although the pattern of distance and RSSI values didn't changed RSSI values seems to be smaller when there is another tag in the environment. Interesting thing is that the other tag which was expected to follow the same pattern, have completely different behavior (line with triangular dots). This means that the radio map generated online failed to be the actual radio map of the tracked tag.

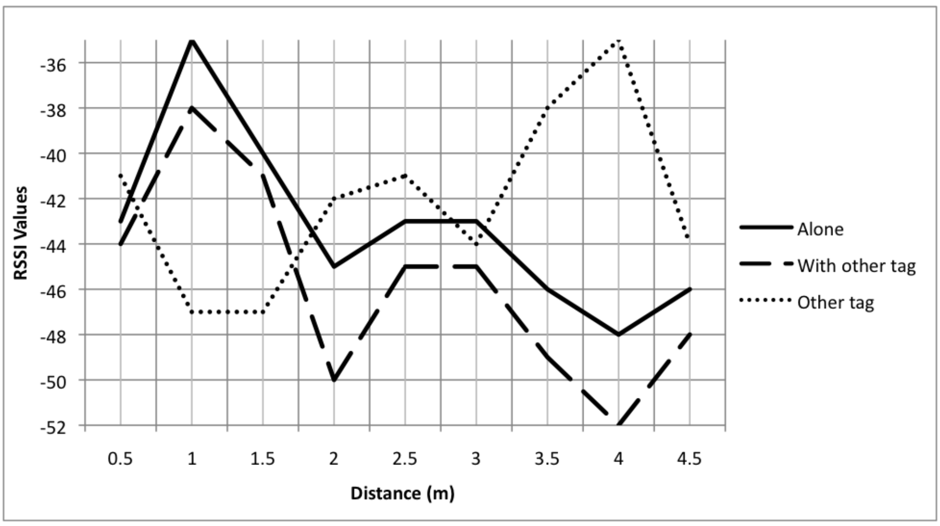


Figure 5.12. RSSI values of difference tags at same locations and from same antenna.

5.2. Passive System

Previous trials were made with active RFID tags. All active tags could be read with the lowest power level from any place in the environment with confusing changes in the RSSI values. As a result, we were unable to utilize power levels and apply constraint-based approaches. Main motivation for the trials with passive tags is to use different power levels for creating fields of detection. Passive system already has constraint of fields of detection within 6x6 m^2. Our aim is to decrease this resolution to 0.5x0.5 m^2. From the results, we saw that the orientation significantly effects the detectability of the tag. What is more, the disturbance of a moving object inside the environment on received signal has much more effects on passive tags then it has for active tags. Although this seems as a weakness of passive system, we have noticed that it can also be used for localization.

Having nearly 57% of body weight as water, a human absorbs most of the transmitted signals and hence avoids signals to reach and induce RFID tag. Likewise, while a person is passing in front of a receiver antenna, the antenna becomes incapable of reading any tag. As a result, the line of sight appears to be a requirement for the passive RFID systems. This requirement relaxes as the distance between antenna and the tag gets larger.

5.2.1. Hardware Selection

The experiment was conducted with Infinity 510 Sirit UHF RFID reader (see Appendix B). This reader has four antennas each capable of both receiving and transmitting. 12 tags were deployed to the environment of 4x3 m^2. Same signal propagation rules applies in this scenario. Figure 5.13 represents the effect of window size. Although the tag is stationary, RSSI readings fluctuate even after using ws.

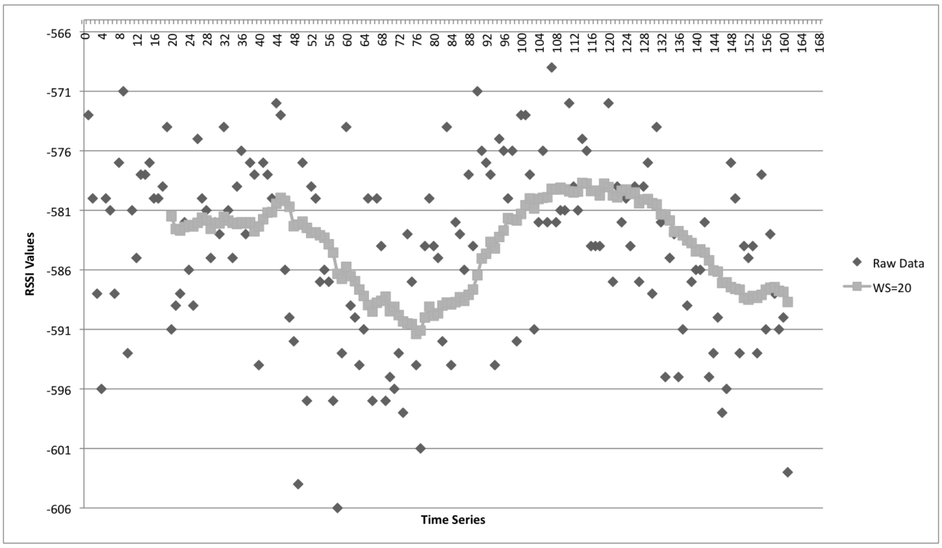


Figure 5.13. Effect of ws on RSSI measurements (passive system).

5.2.2. Pre-application Stage

Orientation of the tag becomes very important in passive system. Tag placement should be done carefully.Tags must be placed such that each one must be visible to all antennas. This requirement is also crucial in order to apply LANDMARC method. Moreover, they should be placed on to the rigid, not often moved items, such as walls and wardrobes. One must be careful not to place a tag close to a metal surface. Figure 5.14 represents the experiment conducted for passive system.

A person wearing a passive tag having id “0” has entered the environment and followed the path shown with arrow in Figure 5.14. Variation in RSSI values are much more higher than it is in active system. In the trials, we used window sizes (ws) of 20 considering responsiveness and scalability for passive system. Although RSSI is used often in various modern communication systems, there are no set standards and as the name RSSI “reflected signal strength indicator” implies it is merely a quantified indicator, not the actual power measurement.

In order to apply LANDMARC method, we should be able to read all the tags at each duration. Signal absorption by the human body causes the tag worn by the

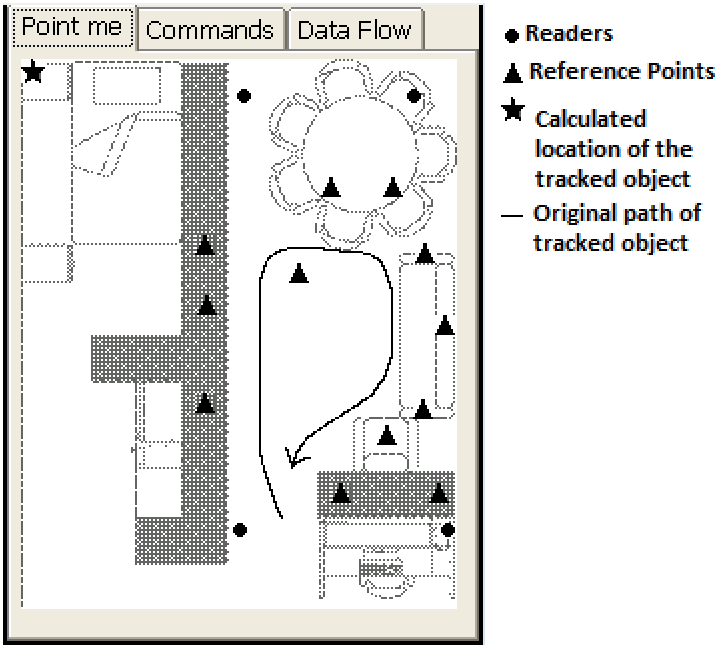


Figure 5.14. Environment and tracked path in passive system.

person and the tags where the person is passing by, undetectable by the reader most of the time and hence making LANDMARC approach not applicable. However, the effects of the motion of the person can be seen from the variations in the RSSI values.

5.2.3. Application and Results

Think of antennas as light sources and the human body as an object that blocks energy to pass through and reach to the RFID tag. Shadowing of the human body, effects the strength of signal received by the tag. Just like you can see the objects under your shadow, because of the multi path propagation of the signal, RFID tag may still acquire enough energy to respond. In addition, the length of the shadow varies according to elevation of the light source.

In TASA [52] (Tag-Free Activity Sensing Using RFID Tag Arrays) system, applicability of shadowing effect in localization has been shown. In the experiment conducted, passive RFID tags has been placed onto the floor in a grid form and antennas are placed to the ceiling of the room. The trajectory of the moving object is constructed in a deterministic way. Multiple antennas has been used and thus a synchronization of readings was required. After synchronizing the readings, based on the RSSI database generated before is used to determine the changed values. The variance in the RSSI can be very high. To remove such outliers appearing because of the variation, active RFID tags has been used. A threshold value has been used to accept a tag as shadowed or not. An average of shadowed tags is assumed to be the current location of the tracked object.

The problem with detecting the shadowing effect is to derive an algorithm that distinguishes the decreases or increase in the RSSI values. If we assume that the tags are placed on the grid with equally placed to one another, diminishing RSSI readings from a tag on a coordinate in the grid means that an object is moving in to this coordinate. Likewise, increasing RSSI readings from a tag on a coordinate in the grid means object is moving out from this coordinate. A changepoint detection algorithm [53, 54] can determine such changes in the expected RSSI values. Adams [55] provides an online change detection algorithm which is suitable for a single time series.

A series of readings $RSSI_1, RSSI_2, ..., RSSI_t$ may be divisible into partitions. We assume that for each partition ρ, data are independently and identically distributed (i.i.d.) with some probability distribution $P(RSSI_t|\eta_\rho)$. The discrete a priori probability distribution over the time interval between changepoints is denoted as $P_{gap}(g)$. Given the data so far observed, we are interested in estimating the posterior distribution over the current run length (time since the last change point). Current run length at time t is represented as r_t. Also notation $RSSI_t^{(r)}$ indicate the set of observations related to run r_t. Assuming that we can compute the predictive distribution conditional on a given run length r_t, we can get the marginal predictive distribution by integrating over the posterior distribution on the current run length $P(RSSI_{t+1}|RSSI_{1:t}) = \sum_{r_t} P(RSSI_{t+1}|r_t, RSSI_t^{(r)})P(r_t|RSSI_{1:t})$. Posterior distribution is $P(r_t|RSSI_{1:t}) = \frac{P(r_t, RSSI_{1:t})}{P(RSSI_{1:t})}$. We can write the joint distribution over run length and observed data recursively by using the Equation 5.4.

$$
\begin{aligned}
P(r_t, RSSI_{1:t}) &= \sum_{r_{t-1}} P(r_t, r_{t-1}, RSSI_{1:t}) \\
&= \sum_{r_{t-1}} P(r_t, RSSI_t | r_{t-1}, RSSI_{1:t-1}) P(r_{t-1}, RSSI_{1:t-1}) \\
&= \sum_{r_{t-1}} P(r_t | r_{t-1}) P(RSSI_t | r_{t-1}, RSSI_t^{(r)}) P(r_{t-1}, RSSI_{1:t-1})
\end{aligned}
\tag{5.4}
$$

Here as it is obvious the predictive distribution $P(x_t|r_{t-1}, RSSI_{1:t})$ only depends on the recent data $RSSI_t^{(r)}$. The prior over r_t which is $P(r_t|r_{t-1})$ has only two outcomes: the run length either continues to grow $r_t = r_{t-1}+1$ or a changepoint occurs and $r_t = 0$.

$$
P(r_t|r_{t-1}) = \begin{cases} H(r_{t-1}+1) & \text{if } r_t = 0 \\ 1 - H(r_{t-1}+1) & \text{if } r_t = r_{t-1}+1 \text{ is odd} \\ 0 & \text{otherwise} \end{cases}
$$

$H(\tau)$ is the failure rate (or hazard rate). Our process has a constant rate of failure with some scale λ.

$$
H(\tau) = 1/\lambda \tag{5.5}
$$

Both prior and posterior of a conjugate-exponential distribution takes the form of exponential family. So, exponential family likelihoods allow us to incrementally calculate statistics as new data arrive. Exponential family likelihoods appears in the form represented by Equation 5.6.

$$P(x|\eta) = h(x)exp(\eta^T U(x) - A(\eta)) \tag{5.6}$$

where

$$A(\eta) = log \int h(x)exp(\eta^T U(x))d\eta \tag{5.7}$$

A normal-scaled inverse gamma distribution is used in our experiments. Normal-scaled inverse gamma is the conjugate prior of a normal distribution with unknown mean and variance which is the case for our RSSI readings.

To experiment the applicability of the changepoint algorithm, we used an environment of sizes 2x2.5 m^2 splitted into grids of size 0.5x0.5 m^2 (see Figure 5.16(a)). We placed a single antenna to the ceiling (see Figure 5.16(b)). In order to increase the performance of changepoint detection, we need to know a realistic value for the RSSI value expectation. We can easily get an intuition about the expectation by getting samples from each tag. Duration of the sampling depends on the performance of the RFID reader. Reading capacity of our reader was 10 ms/tag. Two seconds of polling of RFID tags yields an appropriate estimation for the expected RSSI value of the tag. This time duration is applicable just before the human entrance to the field of interest.

Figure 5.17 depicts the case of a series from readings from a single tag. Changepoint estimations and run lengths with maximum likelihood at time period t are displayed. In the second graph, gray scale region represents logarithm of possibilities, related to run length. There are some intermediate values causing multiple changepoints.

{Initlialize}

$P(r_0) = 1$

$\nu_1^{(0)} = \nu_{prior}$

$\alpha_1^{(0)} = \alpha_{prior}$

$\beta_1^{(0)} = \beta_{prior}$

while observe new RSSI: $RSSI_t$ **do**

{Evaluate predictive probability}

$\pi_t^{(r)} = P(x_t|\nu_t^{(r)}, \alpha_t^{(r)}, \beta_t^{(r)})$

{Calculate growth probabilities}

$P(r_t = r_{t-1} + 1, RSSI_{1:t}) = P(r_{t-1}, RSSI_{1:t-1})\pi_t^{(r)}(1 - H(r_{t-1}))$

{Calculate changepoint probabilities}

$P(r_t = 0, RSSI_{1:t} = \sum_{r_{t-1}} P(r_{t-1}, RSSI_{1:t-1})\pi_t^{(r)} H(r_{t-1})$

{Calculate evidence}

$P(RSSI_{1:t}) = \sum_{r_t} P(r_t, RSSI_{1:t})$

{Determine run length distribution}

$P(r_t|RSSI_{1:t}) = P(r_t, RSSI_{1:t})/P(RSSI_{1:t})$

{Update sufficient statistics}

$\nu_{t+1}^{(0)} = \nu_{prior}$

$\alpha_{t+1}^{(0)} = \alpha_{prior}$

$\beta_{t+1}^{(0)} = \beta_{prior}$

$\nu_{t+1}^{(r+1)} = \nu_t^{(r)} + 1$

$\alpha_{t+1}^{(r+1)} = \alpha_t^{(r)} + 0.5$

$\beta_{t+1}^{(r+1)} = \beta_t^{(r)} + u(RSSI_t)$

{Perform prediction}

$P(RSSI_{t+1}|RSSI_t) = \sum_{r_t} P(RSSI_{t+1}|RSSI_t^{(r)}, r_t)P(r_t|RSSI_{1:t})$

end while

Figure 5.15. Online changepoint prediction algorithm to identify shadowed tags.

(a) Placement of tags

(b) Placement of antenna

Figure 5.16. Positioning of tags and antenna.

Although the algorithm is working real time, we are not able to detect the changes in the time of occurrence. We can understand this from maximum likelihood of run lengths in the second graph of Figure 5.17. Zero run length with maximum likelihood never shows up. Around five readings of RSSI values of a single tag are done within one second duration in an environment with 20 tags. If we assume that 100 readings of RSSI value is needed for determining the changepoint, then there will a 20 seconds of delay in the system to get 100 readings. This is a big value for this system. If tracked subject is moving one meter per second, in an environment of size 6x5 (size of a mid-size living room), our subject can go around the environment nearly twice. As an alternative, we provided an alternative way to decide on whether a tag is shadowed or not.

Alternative to changepoint detection, we used hypothesis testing to define shadowed tags. This system requires to get information pre-sampled from the tags in the environment before starting. 20 seconds of recorded RSSI values of each tag is enough to get an accurate mean and variance of the RSSI values of the tags. It has been shown that the received signal strength usually demonstrates a Gaussian normal distribution [45]. Based on that generalization, our null hypothesis is that RSSI values comes from gaussian normal distribution having mean and variance of the sample ac-

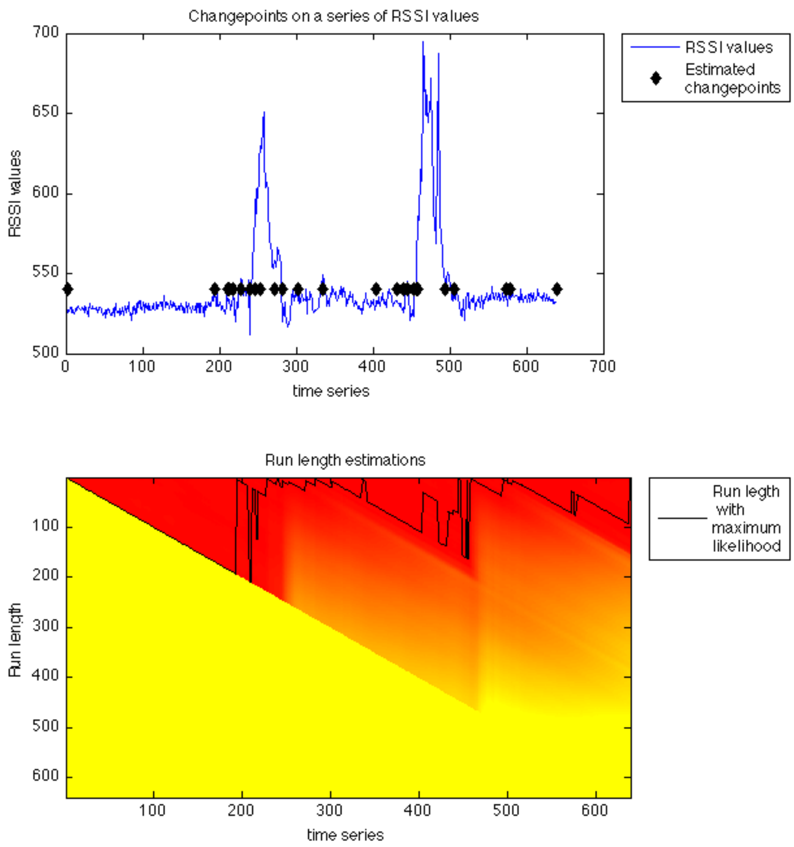


Figure 5.17. Most likely change points calculated from a series of readings.

quired before (Equation 5.8).

$$\begin{aligned} H_0 &: RSSI \geq \overline{RSSI} \\ H_1 &: RSSI < \overline{RSSI}, \end{aligned} \tag{5.8}$$

where $\overline{RSSI}$ is the mean of previously sampled RSSI values and $RSSI$ is the average of the readings which is needed to tested. We have apply $t - test$ to every tag independently.

We can estimate the location of the tracked object, based on the changes in the RSSI of the tags by synchronizing their time of occurrence. In the trial (see Figure 5.18), there are only three tags having identities 15, 18 and 0A are displayed. The tracked person is moving over 15, 18, 0A, 18, 15 respectively. Changes in the RSSI values are clearly describes the movement of the person.

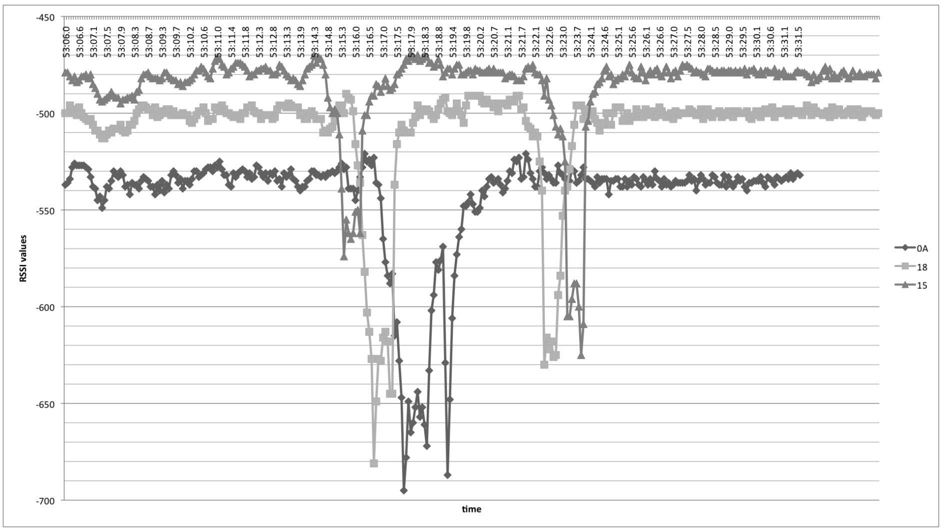
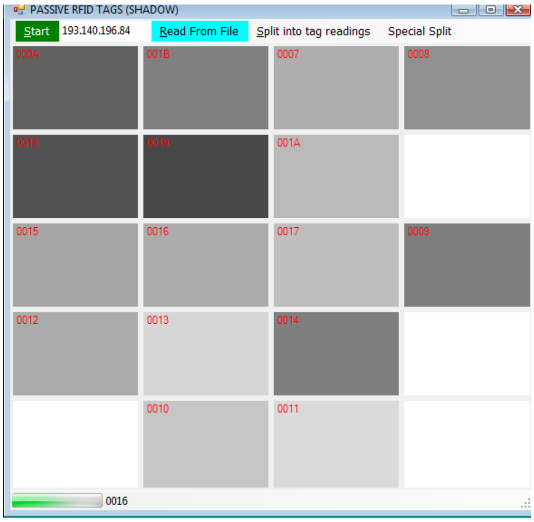
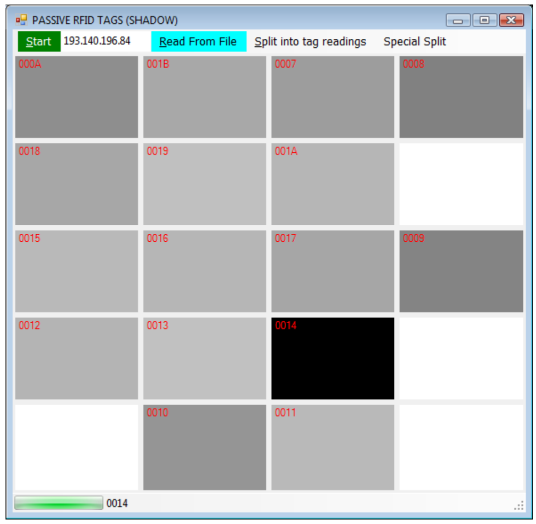


Figure 5.18. Tracked object moves over tag with id 15 through 18 to 0A and then comes back to 15 using the same way.

Length of shadowing is a factor which has an effect on the location estimation. We can estimate the length of the shadow by using the properties of similar triangles. Figure 5.19(a) clearly shows the situation. This is the view of the environment from above. Each cell is ruled by the tag on which they reside. Identities of tags are used as labels for the cells. The antenna was placed over the cell labeled 0017 about 3.5 m above and tracked person with height approximately 1.80 m is positioned on the cell with labeled 0019. Shadow of the person affects the cells with labels 0018, 000A and 001B as well as 0019. Area of the shaded region when person is at cell 0019 is four cells. But when person was at cell 0014, the area was just one cell (see Figure 5.19(b)). When there are more than one cell affected by shadowing, then we should choose the cell which has the closest Euclidean distance to the source as the position of the tracked object.



(a) Tracked object has just moved from cell containing tag with id=0016 to cell containing tag with id=0019. Tracked object is also shadowing the near by tags causing a drop down in the RSSI values. Darker colors represents the effect of shadowing.



(b) Effected number of cells decreases as the object gets closer to the antenna.

Figure 5.19. Effect of distance to the effected number of cells.

We measure RSSI values of a tag and evaluate the change in the readings independent of the other tags in the environment. As a result, we can place to any rigid place in the environment including the furniture except that the item of placement is not made of a lossy dialect element. Even different types of passive RFID tags can be used since readings are evaluated independently.

In the results of our experiments, we have achieved to detect the location of a single tracked object with 0.25 m average error over the area (see Figure 5.20). Accuracy of the system is measured by monitoring and recording the activities in the controlled environment with the help of a webcam. In controlled environments, the algorithms fail to estimate the location for distances larger than 4 m. At this distance, tags orientation and the distance makes the tag nearly impossible to detect.

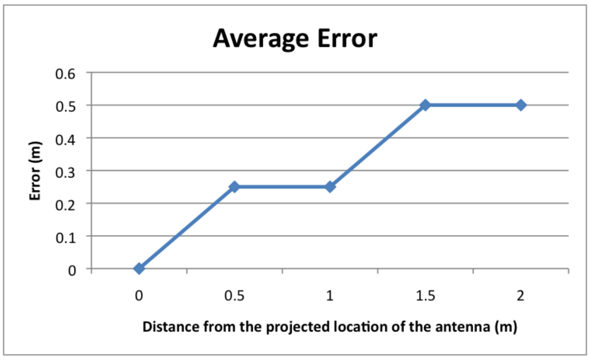


Figure 5.20. Average error in location estimations.

5.2.4. Discussion

In our implementation, the limit was the number of tags available. However, there are some inherited limitations in the proposed system. One of them is the performance of the reader. We made several trials with different configurations to measure readers performance. We have calculated performance measures in terms of readings per second. There are two factors expected to be effective in the performance of the reader: the number of tags in the environment and the number of antennas used. However, it has been discovered that the number of readings per second by the reader is not affected as much as we expected. Figure 5.21 shows total number of readings per second (we are referring it M_1). Antennas access to the control frequency in different time slots, hence scheduling access time of antennas brings an overhead to the reader. In addition to that, number of tags in the detection area of the reader also slightly effects value of M_1. In our trials, we have also calculated the number of readings of one one tag from one antenna in one second duration. We call this performance measure M_2. Although total number of readings achieved by reader is nearly constant, number of readings of one tag from one antenna in one second, M_2, significantly effected by the number of tags in the environment. Table 5.3 depicts the effect of antenna count and number of tags in the environment to value M_2. There is an inverse relationship between the number of antennas and the number of tags in the environment. It has been reported by the manufacturer that average value of M_1 for the reader is 220. We had a different finding. Average of M_1 values after five trials of each configuration

Table 5.3. Readings of one tag per second from single antenna with different configurations.

Tag count	Antenna count			
	1	**2**	**3**	**4**
8	31	16	10	8
12	20	11	7	5
16	17	9	5	3

for approximately one minute duration appears to be 238. Since this value can vary a little bit, we approximated as 240 to make calculations conventional. Equation 5.9 reveals the relation between M_1 and M_2. n and m represents the number of tags in the detection area of the reader and number of antennas used, respectively.

$$M_2 = M_1/m/n \tag{5.9}$$

Consider an environment of size 5x6 m^2. If we were to cover this area with tags separated 0.5 m apart from each other, we would need a total of 120 tags. For better accuracy, we can cover this are with two antennas. For this setting, the Equation 5.9 yields one reading of one tag per second from one antenna. To partially eliminate the effect of outliers in the readings, we can get five samples from each tag. Assuming that our subject is moving at an average speed of 0.5 m/s, which is even slower than an average speed of elderly person at home [56], in a five second duration our subject can move from one end of the environment to another. This sampling rate is insufficient to apply a tracking algorithm, i.e. particle filter or Kalman filter. However, we can increase the sampling frequency, by using readers with better computational power.

In the experiments, our aim was to get the estimate location of the object with a 0.5 m resolution. For this reason, we have created cells of size 0.5x0.5 m^2. In order to

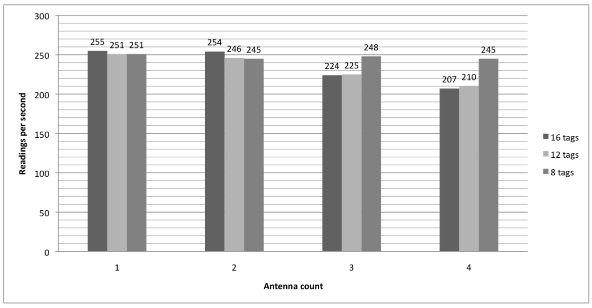


Figure 5.21. Number of readings done by RFID reader per second.

increase the coverage, one can increase the cell size. The shadow of the tracked subject in an environment with cells of size 1x1 m^2 failed to block the signals to reach the tag which represents the cell that subject resides. There is too much space in the cell such that the subject can move inside the cell without effecting the RSSI values of the tag in the cell. In contrast, when the cell size is decreased to 0.25x0.25 m^2, effected number of tags (representing the cells they reside) increases creating outliers related to the location of the tracked subject.

If we want to implement this system to cover the whole house, we may need to deploy multiple readers. In that case, possible inference caused by multiple readers should be considered. Passive RFID reader has a build in functionality that provides synchronization with other readers of its kind. However, this synchronization also has an overhead. Unlike active tags, since the range of an passive RFID reader is six meters and orientation of tag and antenna is so effective that we can create separate detection fields by changing the orientation and/or tuning the power of the antennas. Overhead because of synchronization would be disregarded by this way.

Localization method we used is subject to the main problem of identifying the tracked subject. There are effective methods for in designing wearable RFID tags [57–59]. As the name suggests, designed RFID tags are sensible on a human body.

Another problem is associating RSSI readings with the identities in the environment. It is trivial to detect when there is a single subject. A data association algorithm must be applied when there are more than one subjects are in the environment. We can use existing multi-target tracking algorithms [60, 61] to solve this problem.

6. CONCLUSIONS

We have conducted our experiments with the active RFID system using seven active RFID tags six of which are used as reference and one as the tracked tag. The location estimation is done according to reference points. For that reason, application fails to estimate locations outside the boundaries of convex hull created by the reference tags.

There are other problems related with the real world. RF signals can propagate through concrete walls. Assume that a localization scheme is implemented for each room of a house. It is highly probable to read tags on the other room. In this situation, the system will behave detected tag of the other room like it is one of the tracked objects. This rises another problem of how to decide when the person (tracked tag) first come in.

Passive RFID systems severely suffers from shadowing effect of the obstacles. However, tracking the tags affected by shadowing gives us a good estimate for the location. The performance of the application can be improved by applying particle filter. Particle filter algorithms based on RSSI values [62–64] fail to give sufficient results. This problem is mainly because of the unpredictable behavior of the RF signals in indoor environments. We do not have a good estimator of the probability for tag to be at location x for a given $RSSI$ value. However, by using shadowing effect, we have a clue about the estimate for the position. Hence, we can apply particle filter based on this location estimation and further improve the performance.

There can be other alternative systems utilizing the same idea. Pressure sensors, for example, can be used in a similar way, to estimate the location of the humans inside their homes. Although pressure sensors are cheap, they require wiring in order to send data to a sink, which increases the cost. In addition to that, there is no way to identify the tracked object with pressure sensors. A moved chair or a desk can make the same effect when a person is passing by.

Our study with the passive system covers single target tracking. We have achieved to estimate the location of the tracked object with an average estimation error of 0.25 m within an environment of size 2x2.5 m^2. As a future work, we can embed existing methods like in [65–67] for tracking multiple targets. We can also identify who we are tracking by using specially covered RFID tags that can be wearable by human and still able to backscatter the signals [58].

APPENDIX A: ACTIVE RFID SYSTEM EQUIPMENT SPECIFICATIONS

Table A.1. UDEA RWID-R12 Active RFID Reader Specifications.

Frequency	434 or 868 MHz
Protocol	Property UDEA
Data Rate	38,4 Kbps
Reading Range	20 - 100 m
Number of Antenna Inputs	2
Power	10mW (20dB control possibility)
Supply Voltage	DC 18V - 30V
Communication Port	RS232

Table A.2. TAPA-434 Antenna Specifications.

Operating Freq.	430-435 MHz
Band Width	5 MHz
Gain	6 dBi
VSWR	<1.5
F/B Ratio	>15 dB
Impedance	50 Ω

Table A.3. UTAG-S11 Active RFID Tag Specifications.

Frequency	434 MHz
Protocol	Proprietary UDEA
Data Rate	38.4 Kbps
Reading Range	5-50 m
Antenna	Helical
RF Output Power	10 mW (30 dB cont. range)
Supply	950 mAh / 3 Li
User Memory	64 Byte
Sensor	Temperature
Dimension	52x35x20 m
Weight	25 gr.

APPENDIX B: PASSIVE RFID SYSTEM EQUIPMENT SPECIFICATIONS

Table B.1. Infinity 510 UHF Passive RFID Reader Specifications.

Frequency	860-960 MHz
RF Power	10 mW 1W conducted (30 dBm)
Power Consumption	13W (typical while idle) 34W (typical at 1W conducted output power) 40W (maximum at 1W conducted output power)
Connections	RS-232, Digital I/O, Ethernet LAN
Number of Antenna Inputs	4
Input Voltage	12 to 24 Vdc, 60W
Input Current	2.5A maximum at 24 Vdc 5.0A maximum at 12 Vdc

Table B.2. Antenna Specifications.

Type	PATCH
Frequency (FCC)	860 960 MHz
Polarization	Circular
Gain	7 dBi 1 dBi, max
VSWR, maximum	1.3:1 or less
Axial ratio	1 dB or less
Input impedance	50 Ω (nominal)
Power Handling	10 W
Size	245 mm x 235 mm x 40 mm
Weight	470g

Table B.3. Avery Dennison AD-223 UHF Passive RFID Tag Specifications.

Frequency	Global (860 -960 MHz)
Protocol	ISO/IEC 18000-6C EPCglobal Class 1 Gen 2
Integrated Circuit [IC] Manufacturer IC Name	Impinj Monza 3
Memory	96 bits EPC
Antenna Size	95 x 8.15 mm

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