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RFID Localization using Single Reader Antenna

By

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RFID Localization using Single Antenna

Hamze Msheik

ABSTRACT

In today's modern world it is very important to wirelessly track assets whether small items such as bananas, patients in hospital, to massive mining machines. Radio Frequency Identification(RFID) was recognized as a very effective and easy way to quickly identify such assets. RFID became very popular since it is very cost effective and allowed for automating the process of collecting information about the asset and its. RFID like all other wireless technologies has its short coming when it comes to range and susceptibility to noise. These short coming have made the RFID usage somewhat limited when it comes to its use for Localization. Most extant Localization scheme use Angle of Arrival methodology that results in accurate Localization at an extra cost to the Reader. The use of RSSI has proven to be a cheap solution to the Localization problem since no additional hardware is required, other than the receiver itself. RSS Localization schemes are based on the use of multiple Stationary Antennas and a Single tag placed on the asset. These attempts have been plagued by susceptibility to noise and failed approaching the accuracy of Angle of Arrival method. In this work we propose a novel RFID based Localization methodology. Our scheme is based on Power Map Matching algorithm. The proposed method employs the use of a Single Stationary Reader Antenna and multitags placed on the asset. Unlike conventional Power Map Matching schemes which create the map from actual measurements; the proposed Power Map is automatically generated based on a model. In this work we will justify the proposed Localization scheme analytically and provide numerical and experimental data to substantiate our methodology.

Keywords: RFID, Localization, RSS, Power Map Matching, Single, Stationary, Reader, Antenna

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CHAPTER ONE

Introduction

In modern life the number of items that are handled by any megastore on daily basis has exploded. Locating and tracking such large number of items has become virtually impossible and very expensive using conventional barcode and manual inspection. These databases could only be updated by human intervention and the pace of modern trade made it virtually impossible. If an item is moved and no reference was kept to update the database the item is assumed lost costing many millions of dollars in losses every year. Radio Frequency Identification (RFID) came as a perfect solution to this modern day problem. RFID became very popular since it is very cheap and allowed for automating the process of collecting information about the movement and location of items which meant replacing the inefficient and manually intensive barcode. The update of a database became an instruction or a key-press away. However, using RFID to localize object, has proven to be either expensive or inaccurate in most case. The purpose of this study is to investigate the use of a single stationary reader antenna and multiple tags to improve the localization process. The localization scheme will incur no addition cost to the system. The only additional parts required are passive tags which are commercially available at very low cost. This study will simulate the environment in which the tags are located. The scheme will then take actual measurements and try to localize the tags by matching the result to the simulated values.

In light of this scheme, this paper will go over the literature review followed by a brief explanation about RFID Modeling. Then we will discuss our proposed localization scheme and show the simulated results and compare to experimental results. Finally, we will conclude by a brief assessment of our work and lay the ground for future work.

1.1 Brief RFID History

Identification of items has become a necessity due to the increase in trade volume. The retailer or customer only needed to read a small label to identify the item and who it belongs to. The large variety and number of goods and items that need to be sorted started imposing a huge financial cost. Megastores whether, food, clothing or any other goods were the worst affected by this new imposed cost. Food chains were the first to push for an efficient and cost effective method to automatically identify and sort the components to minimize the time taken up at the cashier and sorting at the warehouse. The answer to this new problem came from a graduate student at the Drexel Institute of Technology by the name of Norman Woodland in 1949. Woodland create what we now call the barcode by using the Morse code and extending it downwards to create the all familiar barcode design that we all identify today. The year 1974 featured the first time use of barcode in supermarkets and ushered in the modern age of consumer product auto-ID. Optical barcode are ubiquitous in consumer retail and are nearly on every commercial item. Later years saw the improvement of this technology into the 2-D barcode that could carry more information in smaller areas. The barcode were hailed as a savior but soon enough people released the limitations of the barcode. The item had to be physically manipulated and aligned for the barcode to be scanned. Anyone who has shopped in a supermarket can stand witness to the many times the bar code was rendered unreadable by unsmooth surface, dust or the wrinkles of the wrapping paper leading to great confusion and delay. A new more efficient and still cost effective solution needed to be found.

1.2 Literature Review

1.2.1 RFID Usage

The new system need to have none of the flaws of optical barcode but all of the advantages. One advantage in particular is COST and second is eliminating the need for line of sight.

RFID is built from a combination of Radio and RADAR technology. In 1899 Nicola Tesla was the first to identify that wireless transmission of power was feasible. Tesla was able to power an 80 Watt bulb at 40 km distance [1]. However, it was until 1948, when Harry Stockman published his work about wireless transmission of power that most scientists started to pay closer attention to this new technology and its applications. RFID tag is made of two complementary parts, antenna which is used to receive and transmit signals and the small chip that would store and analyze the incoming and transmitted data. The first recorded use for RFID was World War II and was used to identify friendly planes from foe[2]. The planes would transmit a signal that would identify which plane it was and thus declaring itself friendly. This system still persists to modern day where RADAR can determine a plane’s speed and direction but not its altitude. The plane uses a transponder that would transmit information about its altitude and plane/flight details.

The modern day use of RFID was first unveiled in Norway in 1987 where it was used as a toll collection tool[3]. RFID tags carry information that would be presented to the interrogator, reader, declaring the type, manufacturer, manufacturing date and any other relevant data to the reader. The reader will then take the proper action accordingly. This information is usually referred to as the tag ID.

The tag communicates with the reader using radio frequency eliminating the need for a line of sight. This meant that the tags could be stored on the inside of the packaging away from tampering and yet be easily read. Another important aspect of using RFID was multitag reading where we can read hundreds of items per second, 1 item per 10 second for a barcode. The customer would walk up to a self-checkout kiosk and scan all of their items while they are inside the shopping cart saving on time and effort. These new systems have been saving millions of dollars in labor and time, they are currently being installed everywhere in the world from libraries, shopping center and even skiing resorts .

RFID has now migrated into every industry where it is been utilized to catalog and brand cattle, it is used to automate automotive industry, forwarding baggage in airports and many others. The RFID business is estimated to be about 7.88$ billion dollar industry in 2013 and expected to grow to a staggering 30.24 billion in 2024[4]. One day with the introduction of cheaper RFID and more accurate localizing schemes, every item whether man-made or natural that is traded will have an RFID attached.

1.2.2RFID Localization Application

Using RFID allows us to automate in many aspects of our life. In order to fully automate the system, we need precise location of the item. This introduced a new problem; the reader can detect that the item is in the proximity but not its exact location. The literature is abundant in research about how to use RFID to localize an item using Time of Arrival, Angle of Arrival, Received Signal Strength Indicator (RSSI) and Power Matching.

Much work has been done around Time of Arrival. It is the bases for GPS localization. Authors of [5]implemented a scheme that combines software-based radio with accurate sampling of clocks used in conjunction with two separate antennas. Their system could localize with sub-centimeter accuracy. The scheme was tested in ideal conditions and never under real life conditions. TOA schemes impose a great additional cost for timing circuits and accurate sampling. In [6]developed a probabilistic sensor model based on the tag'sRSSImeasurement, the antenna orientation, and tag location. A rover would patrol the environment automatically creating a power lookup table. The process was repeated while adding different weight to values received. Using this scheme they were able to achieve 37 cm accuracy. This approach requires sampling the environment for extended period of time. This will make the system inefficient for rapid deployment and does not differ from power matching. In [7] the authors developed an RSSI localization scheme using RFID coupled with Kalman filter. The proposed scheme measured the RSS from nearby tags and was able to attain distance accuracy of 12 cm. The proposed method in[8]fused ultrasonic sensors with RSS reading. The scheme would use the RSS to obtain a rough estimate of location. The ultrasonic sensors information would be then fused with the RSS to improve localization. Using their scheme they were able to achieve 40 cm accuracy. Their proposed scheme incurs an additional cost of the ultrasonic sensors.In[9] the proposed system had passive tags implemented to localize an object. The system deploys a special tag named Sensatag that can detect the communication between reader and tag in proximity. The passive tag's location is known and based on that information the Sensatag can locate itself more accurately and relay that information to the reader. This scheme had an average error of 24 cm. The proposed scheme relied on the design of the Sesatag which is very expensive relative to the use of passive tags. In [22], [23] and [24] the authors all use multiple antennas to improve localization. The signals from multiple antennas are fused to remove false reads. The authors also introduce a new concept of substituting multiple antennas by a beam steered antenna. The fusion between multiple antennas and beam steering allowed for improved performance. The main drawbacks of such techniques is the tremendous amount of processing rendering real time virtually unfeasible and costly antennas.

The main draw of RSSI triangulation is that a passive tag signal is very susceptible to surrounding environmental factors such as obstacles, metallic obstacles would reflect while carbon based obstacles would absorb the signal, other sources of electromagnetic signals and orientation of tag. These environmental factors would have an extreme effect on the received signal strength and thus lead to large errors. The research done attempted to improve the localization by adding more hardware or smart filtering. Extensive studies have been carried out using several antennas to compensate for multipath and tag orientation with somewhat limited success.

We propose that we can improve localization by the use of more tags on the asset. This study will explore the use of multiple tags on asset with a single stationary reader. The method of detection is based on Power Matching Technique. Figure 1 shows an illustration of the proposed system.

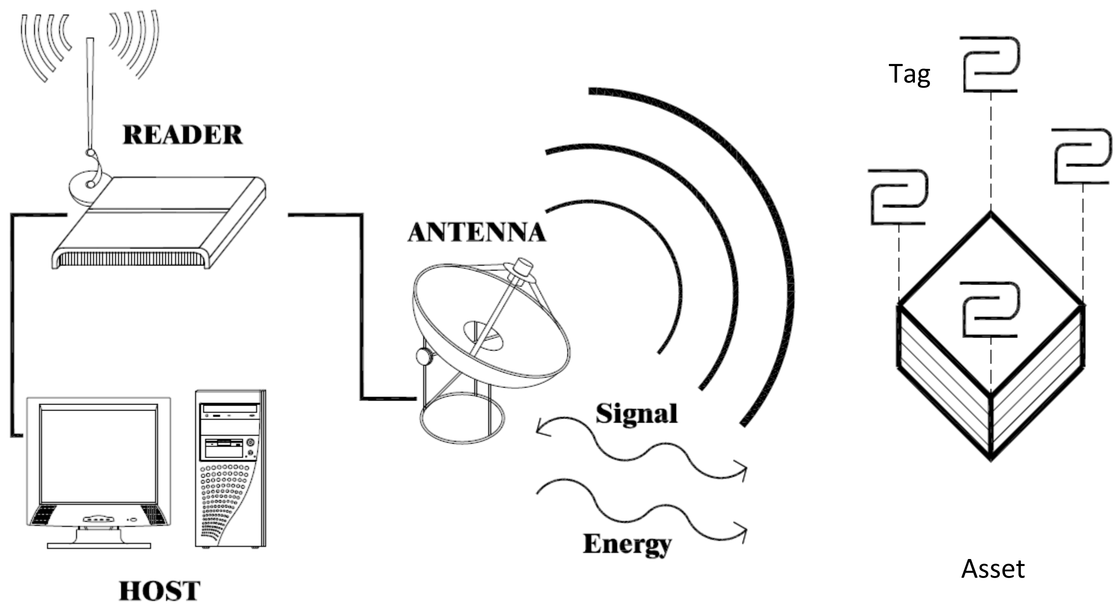

Figure 1. Illustration of proposed system

In this chapter we presented the literature review and a brief history about RFID and its application. Chapter 2 we will explain the working of an RFID system. We will discuss the limitations and the advantages of such a system. Chapter 3 will describe in detail our proposed scheme and all theoretical work. In Chapter 4 we will discuss the numerical results obtained from simulation. Chapter 5 documents the experimental work done as a proof of concept for our proposed scheme. Finally we will conclude with the outcome of this study.

Chapter 2

RFID System

Radio Frequency Identification System (RFID) is made of three interdependent and distinct parts. (1) Tag is the information carrier. It holds all the necessary information to identify the object it is associated with. (2)Reader, also referred to as the RF transceiver is the device used to interrogate, read, or in certain application write to the tag. Finally,(3) the back-end database where the information associated with the tag ID is stored.

2.1 Tag

There has been a new and emerging differentiation of the types of tags. Nowadays the tags are split into two main parts chipless and chipped. The chipless tags are made of a simple antenna or metallic structure. The tag will react to an interrogating signal and its retransmitted or backscattered signal will be used to decode the information encoded within the tag. Chipped tags are made of two parts an Antenna and a small chip attached to the antennas terminals. There are different types of chipped tags and they are usually characterized based on their power sources. The tag comes in three main categories: active, semi-passive and passive tags. Active tags come with an on-board power source and the ability to initiate their own communication; they will broadcast their ID at certain time intervals. These tags are the most expensive and most powerful and can get range up to 1Km and more. Semi-Passive tags also have an on-board power source but do not initiate any communication and will not transmit their ID unless prompted by a reader. The semi-passive has a relatively smaller range than active tags 100 meters typical and cost less than active tags. Passive tags do not have an on-board power source and will receive all their power from the reader. The passive tags have a limited range less than 10 meters, wireless transmission of power, and are the cheapest and most common between all of its siblings.

It is also important to mention that there is a different classification of tags based on their functionality.[10]

Table 1.RFID classes and description

Class 0	UHFI read only, preprogrammed passive tags
Class 1	UHF or HF; write once, read many (WORM)
Class 2	Passive read-write tags that can be written to at any time
Class 3	Read-write with onboard sensors. Can be semi-passive or active
Class 4	Read-write active tags with integrated transmitters.
Class 5	Class 4 tag with more functionality and acts as a power station for other tags

Remark2.1 Tags of Class 0 would be the most suitable tags for localization purposes however this has long been discontinued. The tags that are considered in this thesis are Class 1 tags. Class 1tags, as clearly indicated in table 1, are passive.

2.1.1 *Passive RFID Architecture and Operation*

Passive tag defers from other types is that it has no power source or transmitter. Tags use a rectenna to harvest power from impinging EM waves for powering up their circuitry and use backscatter principle to transmit their information.

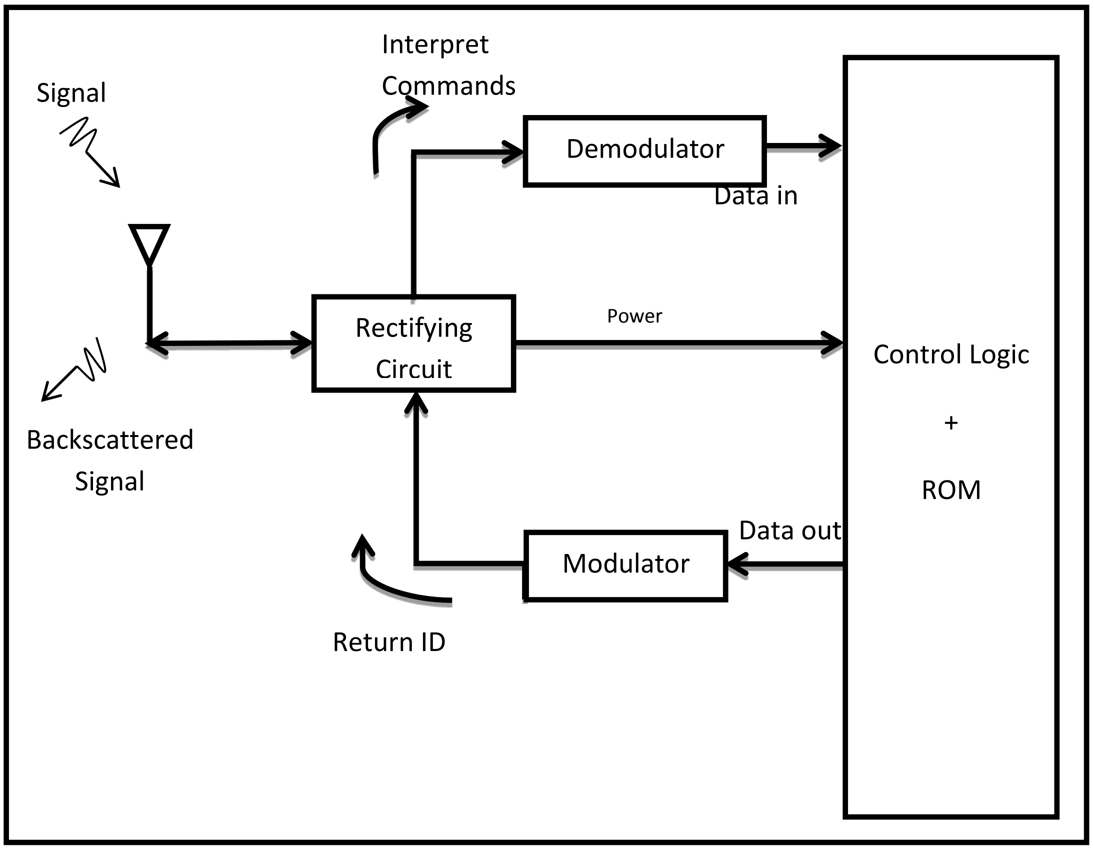

Figure 2.Schematic of a Passive RIFD Tag

The interrogator (reader) will initiate the connection by transmitting a signal. The antenna will acts as a transducer between EM and electrical power. The EM waves bombarding the antenna will be harvested and collected to power up the Tag's operation by using a rectifying circuit (Schottky diodes and a capacitor).

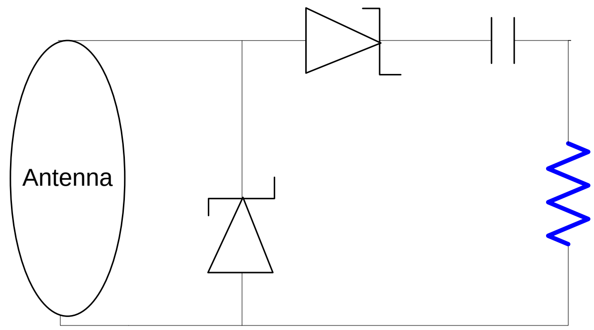

Figure 3.Schematic of Rectifying Circuit

This will supply us withV_{dd}, if the tag responds we have enough power reaching the tag to get a response; important note to make is that these simple power circuits have an over-voltage protection in case too much power was transmitted during interrogation. The amount of power needed by the tag to turn on its IC is referred to as the tag sensitivity and it is the minimum amount of power that the tag needs to respond[10].

The second stage, after powering the circuitry,is extracting the information embedded inside the received signal.

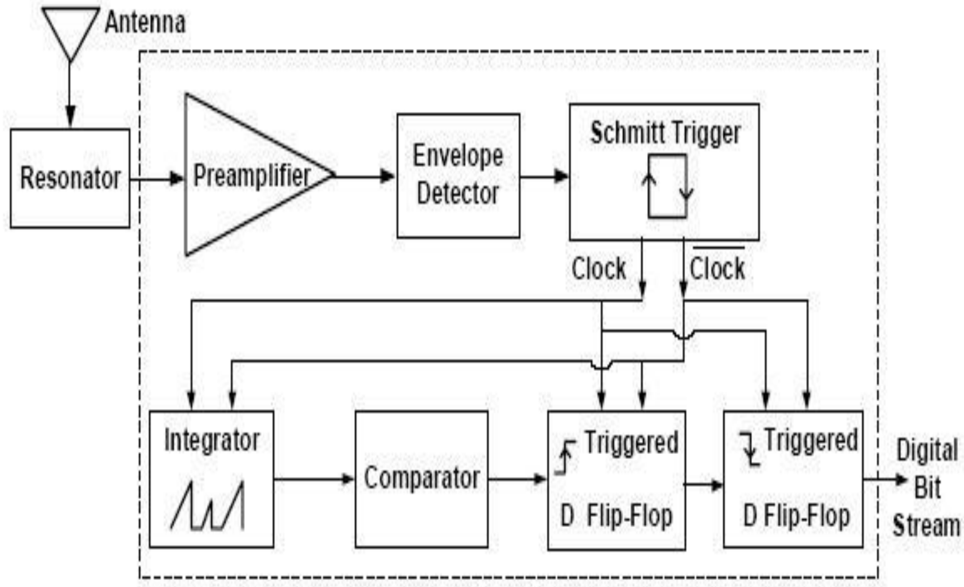

Figure 4.Demodulation stage

The envelope detector will be acting as a mixer it will take a high frequency input and generate a low frequency waveform with the same amplitude modulation as the high frequency input. It is the most common element in low cost radio and AM demodulators.

The Schmitt Trigger will output a high voltage for a sufficient high input waveform and will remain unchanged until a significant change has been seen on the input waveform; this is used to clean up the signal and transform it from sinusoidal to pulse. The signal coming out of the Schmitt trigger becomes the clock for the processing circuitry since it will only change when a change occurs on the input. The signal is then integrated to determine if it is a 1 or 0 and sent out as a digital Bit stream to be analyzed by the logic circuitry and make the necessary operations.

Figure 2 clearly showed that the Passive Tag does not have a transmitter circuitry to generate a signal. The tag makes use of the Backscatter Modulation technique in order to transmit its information. The Antenna absorbed power is given by Frederick Terman[11] to be a ratio between the antenna resistance and load resistance. The power delivered to the antennas terminal (Load Circuitry) to the received power[11] is

$$P_{load} = \frac{R_{load}}{R_{load} + R_{antenna}} P_{antenna} \tag{2.1}$$

$$P_{reflected} = \frac{R_{antenna}}{R_{load} + R_{antenna}} P_{antenna} \tag{2.2}$$

The above equation clearly shows that by changing the Load Resistance we can change the retransmitted power. There are 3 cases of interest for us with the value of R_{load}.

R_{load} = $R_{antenna}$ (match); ρ = 50%

R_{load} = 0 (short circuit); ρ = 100%

R_{load} = infinity (open circuit); ρ = 0%

The above will provide us with the power that the antenna will retransmit. The next step is to relate that to distance, received power and antenna gain to get an idea of what values of RSSI we should expect at the receiver.

$$P_{Int} = \frac{P_{tx} G_{tx} G_{rx} \lambda^2}{(4\pi R)^2} \tag{2.3}$$

$$P_{Ref} = \rho \frac{P_{tx} G_{tx} G_{rx} \lambda^2}{(4\pi R)^2} \tag{2.4}$$

The reflected power infringing on the reader can be calculated by:

$$RSSI = \frac{P_{ref} G_{tx} G_{rx} \lambda^2}{(4\pi R)^2} \tag{2.5}$$

$$RSSI = \rho \frac{P_{tx} {G_{tx}}^2 {G_{rx}}^2 \lambda^4}{(4\pi R)^4} \tag{2.6}$$

The above equation clearly shows the dependency of RSSI on transmitted power. It also shows depends of RSSI on information carried by tag. The relation between RSSI and transmitted power is linear so a 2 dB increase in power transmitted should show an increase of similar magnitude any difference is attributed to multipath effect.

One important aspect to mention is that the above calculation and analyses are made for farfield energy harvesting and decoding. If the tag is too close to the reader the tag is powered by inductive coupling which has a different set of formulas. Due to the non-applicability of near-field analysis it has been omitted in this work.

2.1.2 Radiation Pattern

The formula above clearly shows the dependency on the gain of the tag and antenna. The gain is a direct outcome of the radiation pattern exhibited by the antenna. Radiation pattern refers to the density of the RF power at a certain angle from the reader.The antenna is a passive element and as thus cannot add power to an RF signal. The term gain refers to the antennas ability to direct power in a certain angular direction. The gain is computed as a ratio of how well an antenna can direct the power in a certain angle with respect to an isotropic radiator, radiates equally in all directions, and hence the unit for gain is usually dBi (dB with respect to isotropic radiator though sometimes it can be compared to a dipole antenna and the unit is dBd). One of the most essential parameters to have before we start solving our problem was the radiation pattern for both tag and reader antenna to compensate for them in our code.

The experiments were conducted in a less than ideal situation due to the unavailability of an anechoic chamber or another known antenna to be used in the experiment. The radiation pattern for both tag and reader antenna are shown below as they were obtained experimentally.

2.1.3 Reader antenna

The antenna was placed at a height of 1.8 meters from the ground in open space with no obstacles within 10 meters. This setting was to minimize the effect of the multipath on the radiation pattern. The receiver was placed at 1.8 meters away and Azimuth varied from -40 to +40 degrees due to the limitation imposed by the equipment.

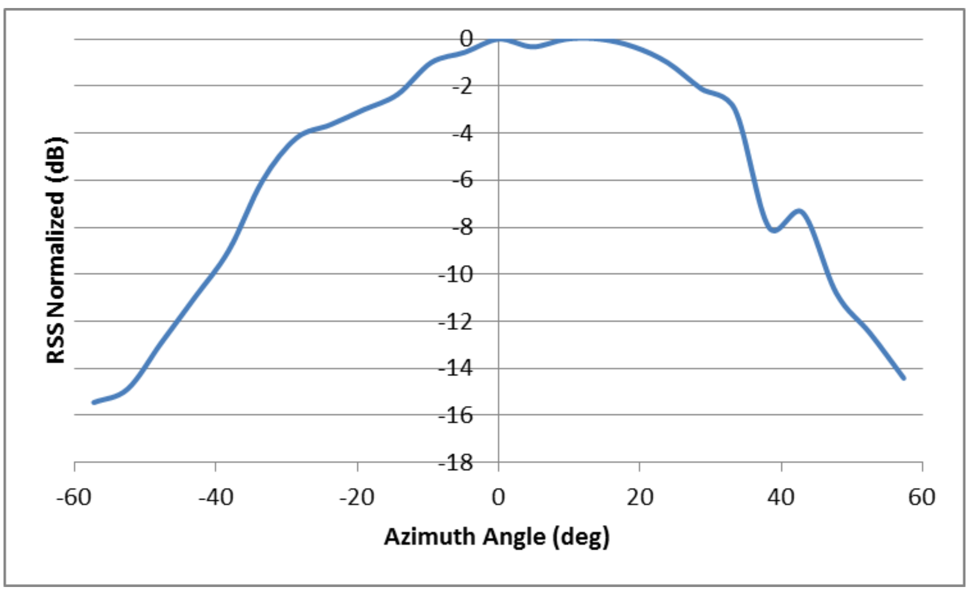

Figure 5.Reader's Antenna Radiation pattern

Figure 5 shows the radiation pattern of the antenna used. The first thing to notice is the antenna has max directivity not at 0 degrees but at 7.5 degrees. This slight deviation from the 0 degrees is common with antenna. The antenna is symmetrical around its center of radiation (7.5 degrees). The rest of the study will refer to the center of radiation referencing the 7.5 degrees not 0 degrees. The reader antenna we have used has a gain of 12dBi and a 3dB beam width of 28 degrees.

2.1.4Tag Antenna

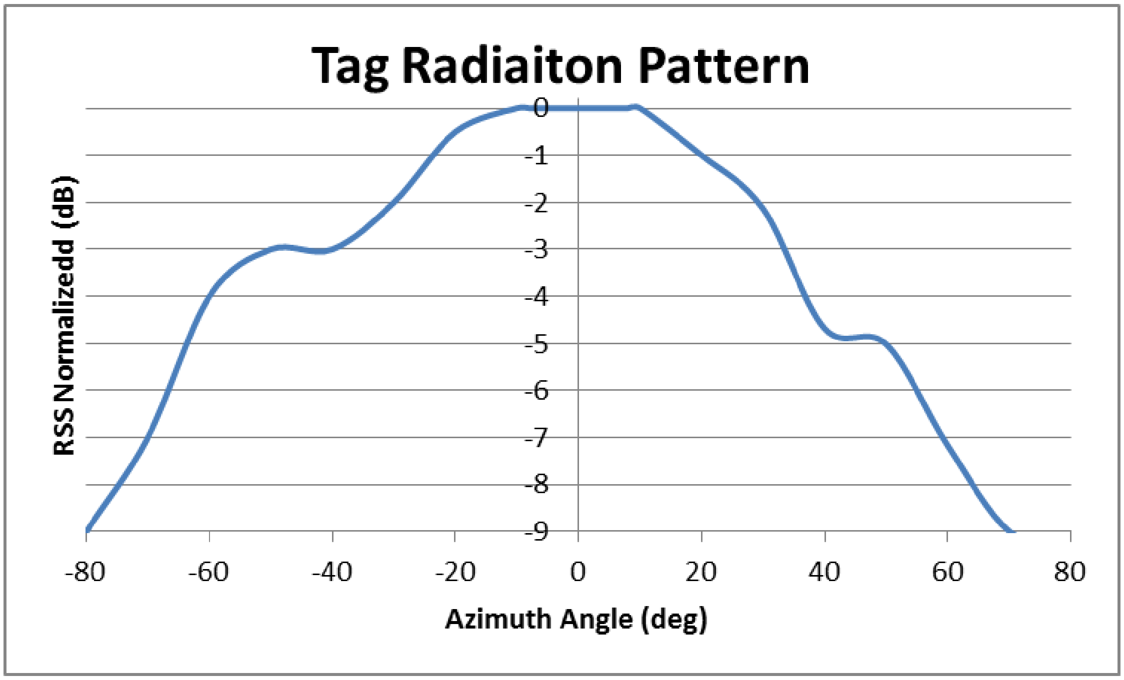

Figure 6.Tag's Antenna Radiation pattern

The radiation pattern of the tag clearly shows that a somewhat directive antenna is being used instead of the typical dipole. In a typical dipole one would expect a circular radiation pattern which is not the case as shown by figure 6. A circular radiation pattern would have equal amount of power radiate on all values of azimuth. The tag's 3dB beam width is 60 degrees. Since we were unable to experimentally determine the elevation radiation pattern we cannot determine the exact gain of the tag.

Remark 2.2 The radiation pattern exhibited by both reader and tag antenna is asymmetrical. This will be a source of error in power map matching. The scheme is based on symmetry of both sides of antenna and tag.

2.2 Readers

The reader is a mixed signal circuitry that will interact with RFID tag using RF signals. The reader has an RF front end that will convert its digital information into RF signal as well as supplying power to the passive tag to operate. The reader back end includes a small processor and memory to store and process data.

The transmission of the signal from antenna to tag is called the “forward channel” while the backscattered signal or echoed is referred to as the “backward channel”. The Reader is characterized by its operational frequency, the frequency that it uses to interrogate the RFID tags, and its output power and sensitivity. Sensitivity of a reader refers to the minimum power that a reader needs to be able to properly decode received signal. If the back scattered signal goes below that threshold the reader can no longer detect the tags response. The reader can be handheld, RFID wand, or stationary based on the application.

2.3 Backend Database

The reader and tag will get a look up key. This RFID ID is usually a 96 bit binary code. However, the code carries no meaning. It is the backend that connects this private key to some information stored in its database. The database must be created and referenced properly for proper utilization of an RFID system. Some books and papers might not mention the Backend Database since it is assumed that the reader has the necessary information to make a decision based on the tag's signature.

2.4 Interrogating multiple tags

Passive tags are interrogated tens and even hundreds at a time. When multiple tags respond at the same time their signals will interfere and cause the data to be lost. The reader implements a very well established and widely used random back-off period to avoid collision. The tag will chose a random integer and will wait for that amount of time before it starts modulating the incoming signal in order to avoid collision. Other more complicated schemes have been implemented where the reader will query a certain tag by using their ID and will ask for a response from that specific tag but not widely popular since most readers do not know which tags are in the vicinity.

2.5 Frequency and Regulations

Most of the RFID systems operate in the Industrial-Scientific-Medical (ISM) band which is free to use for short range and power systems. These bands are defined by the International Telecommunication Union (ITU). The two major bands used by RFID systems in the USA are the 13.56 MHz and 902-928 MHz while some variation on these might exist in different countries based on their spectrum licensing. The maximum power and antenna associated with that power is clearly defined in the guidelines of the ITU. A quick rule of thumb is that the Equivalent Isotropic Radiated Power (EIRP) should not exceed 36 dBmfor linearly polarized antennasand 39dBm for circularpolarization [12].

$$EIRP = P_T + G_a \tag{2.7}$$

Where P_T is the transmitted power, G_a is the transmitting antenna gain. As an example in the 920-926 MHz range the power from the reader should not exceed 1 W (30dBm) while the antenna gain should not exceed 6 dB for linear antennas and 9 dB for circular. The bandwidth per channel is limited to 500 KHz for both forward and backward channels with a maximum time of 0.4 seconds per channel. The power and gain are interchangeable where one can lower the gain and use higher transmitted power. These values are based on Australian standards and might differ slightly from one nation to another.

2.6 Localization challenges

As discussed above, all RFID-based object localization techniques have inherent position estimate errors due to various external (environmental interferences) and design (reader can only provide integers and has small range) factors. This section will discusskey factors that could contribute to localization error.

2.6.1 Interference and RF occlusion

Environmental factors such as noise and obstruction by carbon or metal based objects can cause radio wave scattering and attenuation. This in turn can result in localization errors. Deploying more tags in the region of interest can reduce adverse effects due to interferences and occlusions. The use of different tags might lead to a few being affected while the others would have a line of sight to reader. At the very least the geometric relation between the tags can allow us to improve our localization and reduce error.

2.6.2 Tag spatiality

RFID-based object localization techniques typically utilize reference tags within testing space. They will read these tags to determine the state of the medium and will try and match the current reading to its closest stationary tag. The system we have used will not attempt to use these stationary tags but instead investigate the optimal spacing and configuration for onboard tags for optimal results.

2.6.3 Tag orientation

The orientation of the tag significantly affects the power received by the reader. This is explained in chapter 2section (1.4). The tags that might be used on the vehicle can be any type or shape and can have any direction. Due to the complexity of the work and limitation of time and resources we have opted to remove this variable and consider our tags as isotropic radiators.

2.6.4Four tag calibration

The system we are testing will make use of 4 calibration tags. These tags will supply the reader will all the necessary information about the environment. The tags are placed in the main beam of the reader antenna at incremental distances from one another. The tags will be used to calculate the loss factor in the environment and Sigma, standard deviation for the noise.

CHAPTER THREE

PROPOSED Localization Method

This chapter formally presents the statement of problem considered. In this chapter we introduce how to create the power map virtually. The second part discusses the error introduced due to power and distance quantization theoretically.

3.1 Problem Statement

The problem setup is based on the following assumptions Problem 1:.

A1.The coordinate of the stationary antenna are known

A2.The tags location to one another is known.

A3.The asset is within the reader's operational range and antenna beam width.

A4.The reader antenna and tag are placed on the same plane.

A5.The tags radiation pattern is assumed to be isotropic.

Based on assumptions (A1)-(A5) ,develop an algorithm estimating the coordinates and orientation of the asset.

3.2 Tag localization algorithm

RSSI measures can be modeled as a nonlinear function of the distance between the antenna and asset, the asset rotation angle, and azimuth angle formed by the asset and the antenna – assuming that tags are isotropic and their locations within the asset frame are known. Consequently, at least three tags placed at different locations on the asset are required to estimate the position of the asset. However, due to error in RSSI measurements, more than three tags may be required in order to have good localization estimates. The knowledge of the tags locations with respect to the asset frame provides useful information due their geometric constraint. Directly solving such constraint nonlinear equations in presence of measurement errors may lead to infinite solutions. Another approach to the localization problem is by indirectly solving such linear equations. In particular, a grid-like power map in the range of the antenna is generated using the nonlinear functions and the RSSI measurements are simultaneously matched to their closest corresponding values. This approach can be considered as quantizing the solutions hence limiting the number of solutions. The latter approach is adopted in this manuscript and detailed in this section.

3.2.1Lookup Table Builder

The proposed scheme relies on power map matching. Unlike other power map matching algorithms [6] where RSS is measured and recorded for all locations, the proposed method simulates RSS based on radiation pattern specific to the proximity of the employed antenna and tags. The employed lookup table is based on the following parameters, P_0, d_0, n and radiation pattern, keyed into equation 3.1[14]. The adopted measured signal level model is based on the average received signal decreasing logarithmically with distance with log-normal shadowing. In particular, at a specific distance separation between antenna and tag, d, the measured signal levels (or RSSI) in dBm units, $P_r(d)$, have a Gaussian distribution about the path loss distance-dependent mean. Consequently, the signal level model is given by [13]

$$P_r(d)[dBm] = P_t[dBm] - PL(d)$$

$$PL(d) = \mathrm{E}[PL(d_0)] + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma$$

where E[.] is the expectation operator, P_t is the tag transmitted backscattered power, $PL(.)$ is the average large-scale path loss, d_0 is the close-in reference distance, n is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable in dB with standard deviation σ also in dB.

$$PL_i = PL_0 - 10n\log_{10}(\frac{d_i}{d_0}) - PL_{angle\ i} \quad (3.1)$$

$PL_i$is total path loss measured in Decibels at a location i. PL_0Path loss at the reference distance d_0 and angle 0 (The transmitter is sitting dead center in main beam of receiver's antenna; it has the maximum gain at that point)$PL_{angle\ i}$Angle that location 'i' makes with the main radiation beam of the receiver's antenna.The lookup table presented is 3 dimensional. The first dimension refers to distance between the transmitter and tag. The second dimension is angleφ that the transmitter makes with the Main radiation beam. The third dimension(θ), is the rotation that the asset experiences. The rotation will not play a role when we are measuring a single tag. However, it will have a huge impact on RSSif more than one tag as illustrated by the schematic below.

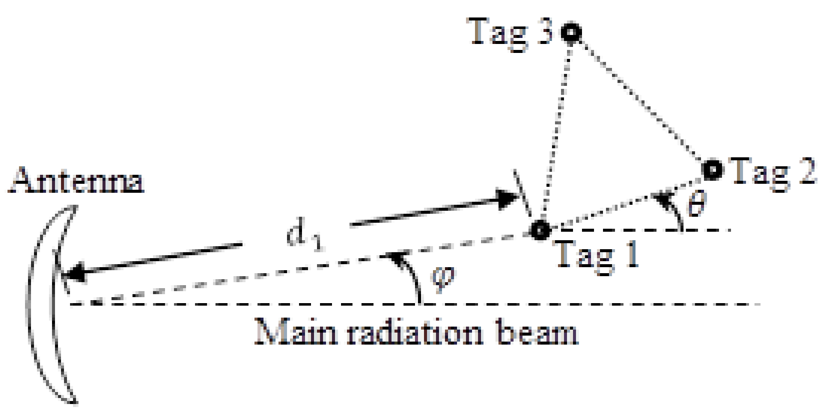

Figure 7.Illustration of the employed parameters

To determine the best condition to be used in our experiment we have created a simulator to generate different environments and setups. The minimum reading distance is considered to be the farfield of the antenna calculated by: $d_{min} = \frac{2L^2}{\lambda}$ where L is the antenna size; λ is the wavelength. The maximum reading distance is referred to as d_{max}. Similarly we declare φ_{max} the angle at which the losses exceed 12 dB, φ_{min} is the angle where we have the maximum directed power. θ_{max} and θ_{min} are define from 0 to 2π .

The first point of interest was to determine the accuracy of the Lookup table. The Lookup table simulator cannot sample every point in space; this would lead to an infinite matrix and cannot be processed. The system will choose a sample space of a certain size to represent the space. The number of points chosen to represent the distance, φ and θ sample spaces is Q.

$$\begin{cases} \Delta d = \dfrac{d_{max} - d_{min}}{Q} \\ \Delta\theta = \dfrac{\theta_{max} - \theta_{min}}{Q} \\ \Delta\emptyset = \dfrac{\emptyset_{max} - \emptyset_{min}}{Q} \end{cases} \tag{3.2}$$

Δd distance increment in the lookup table. $\Delta\theta$ rotation angle increment in the lookup table. $\Delta\emptyset$ angle with main beam increment in the lookup table. The documentation below is an illustration of the lookup table building algorithm.

Point (1, 1, 1)

1. The lookup table builder will choose the minimum allowed distance for Tag 1
2. Choose the minimum angle φ
3. Choose the minimum rotational angle θ

4. Compute the locations of Tag2, Tag3 and all others if exist based on predefined geometric constraints
5. Compute the expected received power for each tag using equation 1.
6. Save the power values in the lookup table indexed by the values of *d, φ, θ.* For point 1index is 1,1,1 for all tags)

Point (1, 1, 2)

1. Increment$\theta$by $\Delta\theta$
2. Repeat from step 4 in Point 1

Point (1, 1, Q)

1. Use $\theta = \theta_{max}$
2. Repeat from step 4 in Point 1

Point (1, 2, 1)

1. Incrementφ by $\Delta\emptyset$
2. Repeat from step 4 in Point 1
3. Repeat for all θ
4. save in appropriate locations
5. Repeat from step 1 while $\varphi \neq \varphi_{max}$

Point (2, 1, 1)

1. Increment$d$ byΔd
2. Repeat from step 4 in Point 1
3. Repeat for all θthen for all φ

4. save in appropriate locations
5. Repeat from step 1 while $d \neq d_{max}$

3.2.2Locating a match

The second step is to take a reading. The reading is then sent to our Match locater. The match Locator is a simple comparator. The locator will consider a point indexed by (i, j, k) as a possible match if the powers (Power Tag1, Power Tag2, etc…) saved within the lookup table satisfy the following condition:

$$\|p - \hat{p}\|_{2\ (i,j,k)} = \sqrt{\sum_{m=1}^{M} (p_{m,(i,j,k)} - \hat{p}_{m,(i,j,k)})^2} \leq C \qquad (3.3)$$

M is the maximum number of tags being used

p_{mi} is the simulated power for tag *m* in location *i*

$\hat{p}_{mi}$ is the measured power for tag *m* in location *i*

C is a positive constant. However, the choice of *C* depends on the *M* and σ. In particular, *C* is chosen larger for larger values of *M* and σ. The relation between them is described as follows

$$C = \sigma\sqrt{M} \qquad (3.4)$$

The received signal strength depends on two factors: the distance and angle with respect to receiver. If a power *P* is received then there are two boundaries to this problem. The first where the Angle is 0 degrees and distance is the only contributor to the loss experienced by that signal. The second boundary is the tag being at an angle φ and the distance corresponding distance. These two are the boundaries condition and a large set of values exists in between where a compromise between distance and angle exists. An easier way is to imagine a tag at distance d and angle 0 we will call this point location 1. The measured power at location 1 is P_1. If we wanted to move this point closer to us but keep the same power reading the only choice would be to increase the angle to generate a loss equal to the gain due to the smaller distance. This relation is very clear from equation 3.1[14].

$$10n \log_{10}\left(\frac{d_i}{d_{i+1}}\right) = PL_{angle\ i} \tag{3.5}$$

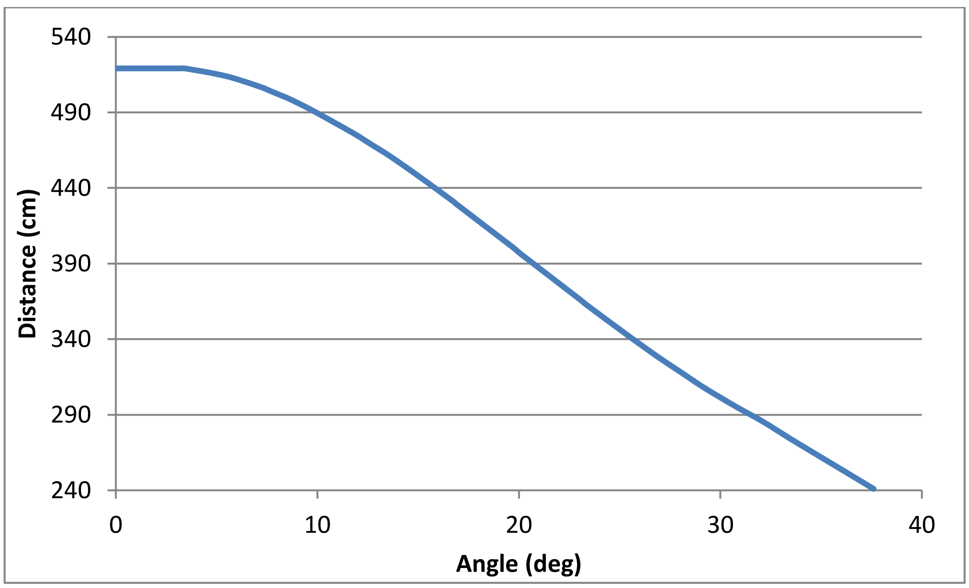

Figure 8.Relation between Angle and Distance for a solution

The figure above shows the solution set for a certain P_i. The angle parameters are the location in 2 dimensional array and not values. The increments are already known and we have set them as described in equation 3.2, $\Delta d = \frac{d_{max}-d_{min}}{Q}$; $\Delta\emptyset = \frac{\emptyset_{max}-\emptyset_{min}}{Q}$.

$$10n\ \log_{10}(\frac{d_{i-}\Delta d}{d_0}) = PL_{(angle\ i+\Delta\emptyset)} \quad (3.6)$$

Equation (3.6) shows that to keep a constant power P_i we have to follow the curve defined by that relation. Locating asset in few milliseconds is essential for a real-time application. Matching algorithm implements a smart search algorithm leading to significant speedup. For a specific power $\hat{p}$ numerous solutions exit. The solution set satisfy Equation (3.6). This implies that for a constant $\hat{p}$ as distance varies resulting in power increase denoted by $+\partial_p$ in RSS, φ must be changed to counter this increase by introducing a power change of magnitude $-\partial_p$.

for($\theta = 0$; $\theta < 2\pi$; $\theta = \theta + \Delta\theta$)

{

for($d = d_{max}$; $d \leq d_{min}$; $d = d - \Delta d$)

for ($\varphi = 0$; $\varphi \leq \varphi_m$; $\varphi = \varphi + d\varphi$)

if ($\|p_k - \hat{p}_{mi}\|_{2\ (i,j,k)} \leq C$)

Compute slope $d\varphi$ using $10n \log_{10}(\frac{d_i}{d_{i+1}}) = PL_{angle\ i}$;

Compute the number of steps $X\varphi$ such that $\|p_k - \hat{p}_{mi}\|_{\ (d,\varphi,\theta)} \leq C$;

redefine search parallelogram circumscribed by $d_{max}, d_{min},$ and $\varphi_m = \varphi + X\varphi$;

Save matches to correct locations.

end if

if $d = d_{min}$ reset search space and repeat until $\theta < 2\pi - \Delta\theta$

3.2.3 Sorting

The last step is to sort the matches based on the least error. The error is the mean square root for all errors for power measurements. The system will sort the values based on the lowest error first. We have noticed that we are only interested in the best match and as a result the system will only locate the minimum error entry and report it back thus speeding the operation further. Figures 9 and 10 show the power error as distance and angle is varied.

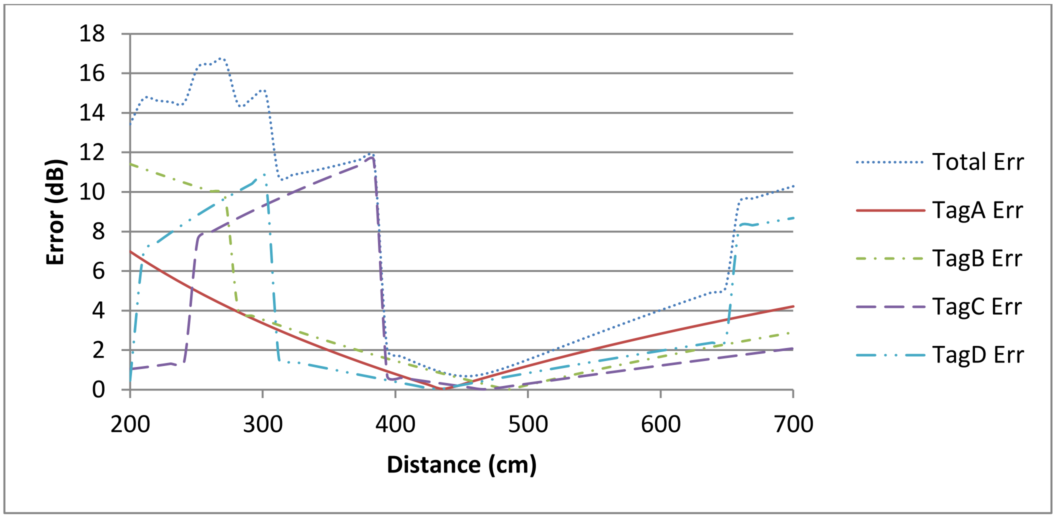

Figure 9. Error (dB) vs. Distance (cm)

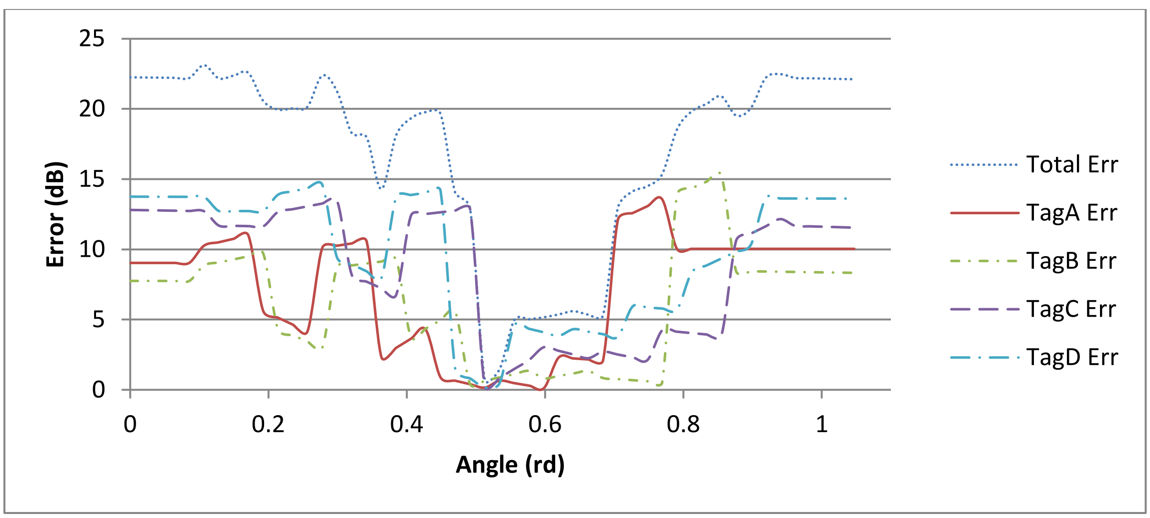

Figure 10. Angle vs. Distance solution plot

We can clearly see from the graphs that the global minimum is not located at a local minimum of any point. This is a clear indication on the impact of using multiple tags for localization.

3.3 Quantizing error due to Power and Grid Quantization

The error resulting from mapping the large set of point in continuous space to the smaller set created in our Lookup table is called Quantizing error. The graph below shows the Quantizing error vs.*Q* . The reader we used has a maximum reading range of 7 meters and farfield at 1.5 meters

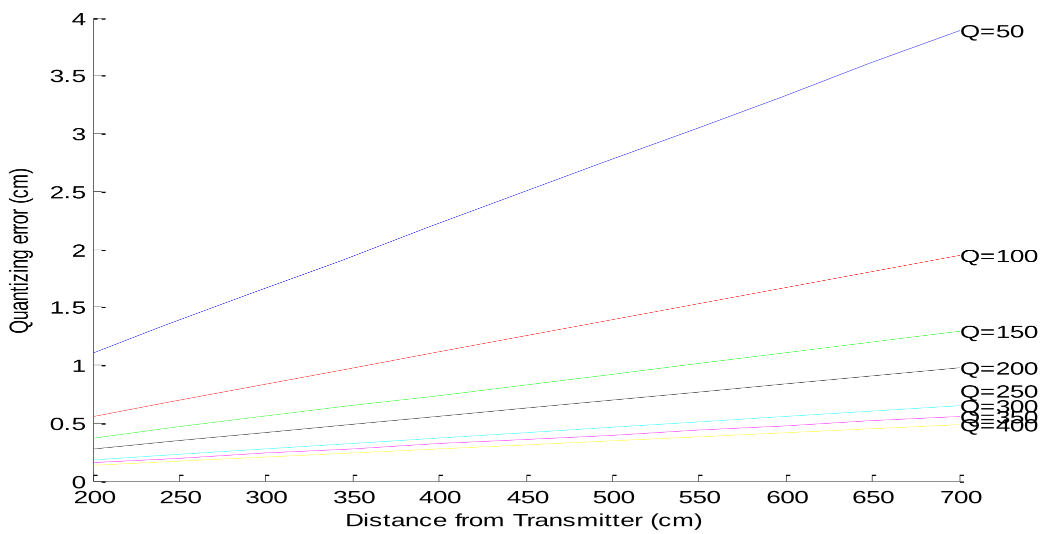

Figure 11.Quantizing Error (cm) vs. Size of Lookup Table

The graph clearly shows that as *Q* increases the Quantizing error will decrease. It is also apparent that *Q*=50 is a fair approximation of space, in this case. An increase in *Q* does not significantly improve the Quantizing error but will exponentially increase the matrix size and processing time. Size of matrix using *Q*=50 is 50^3while for *Q*=100, size =100^3.

It is clear that the improved accuracy of 1 cm is not a good trade for octuplet the processing time.

The reader itself will introduce an error we will call Power Quantization Error (PQR). The reader does not support floating point and has a limited range within its ADC. This results in an error due to its inability to properly represent the received power. We will show the minimum acheivable error due to Quantizing error and PQR.

$$d_i = d_0 + k\Delta d \tag{3.7}$$

$$d_{i+1} = d_0 + (k+1)\Delta d \tag{3.8}$$

$$P_{Q-1} = P_0 - 10n\log_{10}\left(\frac{d_{Q-1}}{d_0}\right) \tag{3.9}$$

$$P_Q = P_0 - 10n\log_{10}\left(\frac{d_Q}{d_0}\right) \tag{3.10}$$

d_i is the distance from receiver at point *i*

d_{i+1} is the distance from receiver at point *i+1*

P_Q is the power received from the furthest point in our enviroment

P_{Q-1} is the power received from the one before furthest point in our enviroment

$d_{Q-1}$is the distance between receiver and the point before furthest point in enviroment

$d_Q$is the distance between receiver and the furthest point in our enviroment = d_{max}

n is the path loss

Q is the number of points in our lookup table

The last two points are the most difficult for the reader to differentiate. The power difference between the two will be the lowest change experienced in our lookup table. The error due to the quantization error of power map is reffered to E_{PQ}. This will dictate that for proper identification the power differnce between any two points has to be equal or a multiple of half the reader's resolution reffered to by ΔP. The reader's resolution is the minumum amount of power change the reader can detect. The variation in power below ΔP will not induce a change in the reader's output.

$$P_{Q-1} - P_Q \geq k\Delta P \tag{3.11}$$

Using equations 3.6, 3.7, 3.8, 3.9 and 3.10 we can deduce

$$\left(P_0 - 10n\log_{10}\left(\frac{d_{Q-1}}{d_0}\right)\right) - \left(P_0 - 10n\log_{10}\left(\frac{d_{max}}{d_0}\right)\right) \geq k\Delta P \; where \; k = 1 \ldots \ldots K$$

$$\frac{d_Q}{d_{Q-1}} = \frac{d_{max}}{d_{Q-1}} \geq 10^{\frac{k\Delta P}{10n}}$$

$$d_{Q-1} \leq d_{max}C_1 \; such \; that \; C_1 = 10^{-\frac{k\Delta P}{10n}} \leq 1 \tag{3.12}$$

$$\Delta d = d_{max} - d_{Q-1} \geq d_{max}(1 - C_1) \tag{3.13}$$

$$Q \leq \frac{d_{max} - d_0}{\Delta d} = \frac{d_{max} - d_0}{d_{max}\left(1 - 10^{-\frac{k\Delta P}{10n}}\right)} \tag{3.14}$$

Equation 3.14 shows an upper bound on Q or lower bound on Δd. The number of increments that can be used for a certain distance cannot be larger than this value. The choice of a larger value of Q will risk compromising the readers ability to differentiate the distance steps made. A smaller Δd translates into a lower power difference. Power difference lower than ΔP or not a multiple of $k\Delta P$ will not be detected properly. This will contribute in additional error. This will minimize the power quantization error; however, there will always be quantization error due to previous steps being a fraction of ΔP.

The next step is to find a lookup table$Q$ based on distance quantization errror (E_{MQ}). The increase in Qleads to a decrease inE_{MQ}. The graph below shows the relation between $E_{PQ}, E_{MQ}$and $Q. E_{MQ}$ Error due to distance quantization.

$$E_{MQ} \leq \frac{\Delta d}{2} = \frac{d_{max} - d_0}{2Q} \tag{3.15}$$

Worst condition is when Error is the equal to half of step size. We need to choose Q such that we minimize that error. Q has to be chosen such that

$$Q \geq \frac{d_{max} - d_0}{2E_{MQ}} \tag{3.16}$$

Equation 3.16 provides us with an lower bound for Q and a upper bound for Δd. Larger values of Q will allow us to minimze the error due to Distance Quantization.

Equations (3.14) and (3.16) relate any enviroment (*n*) with reader's resolution (ΔP) and maximum deployment distance (d_{max}) to calculate the minimum error experienced by the localization scheme. The minimum error also dictates the use of *k*=1. This will result in the minimum error without adopting some filtering or averaging technique to reduce the effect of power quantization.

3.4 Conclusion

In this chapter we have presented and explained our proposed methodology. We started by explaining the inner working for creating a virtual power lookup table. Second, we explained the theory behind the speedup techniques deployed. The speed up makes the system real time compatible. Finally, we derived a new relation that bound error to reader's sensitivity, range and environment.

Chapter 4

Numerical Results

In this chapter we will discuss the simulation results and the lessons learned. First, we will study the improvement of using multiple tags and the area they cover. The third part will focus on the error vs. standard deviation of the noise for different tag configuration. Last, we will study the effect of oversampling on the error in localization.

4.1Number of Tags and Area versus Error

The first objective is to determine the optimal number of tags to be used and the optimal inner tag spacing. The inner tag spacing was kept equal between all tags; AB length is equal to AC and BC and so on. The trigonometry used for the tags is shown below. The results of using 3 and 4 tags are documented. The error using single or 2 tags were very large that we opted to disregard using 1 or 2 tags. The system was feed 50 random points with distances ranging from 200 cm to 700 cm and angles varying from -10 to 45 degrees (the reader antenna is symmetrical; we do not need to test from -45 to 45).

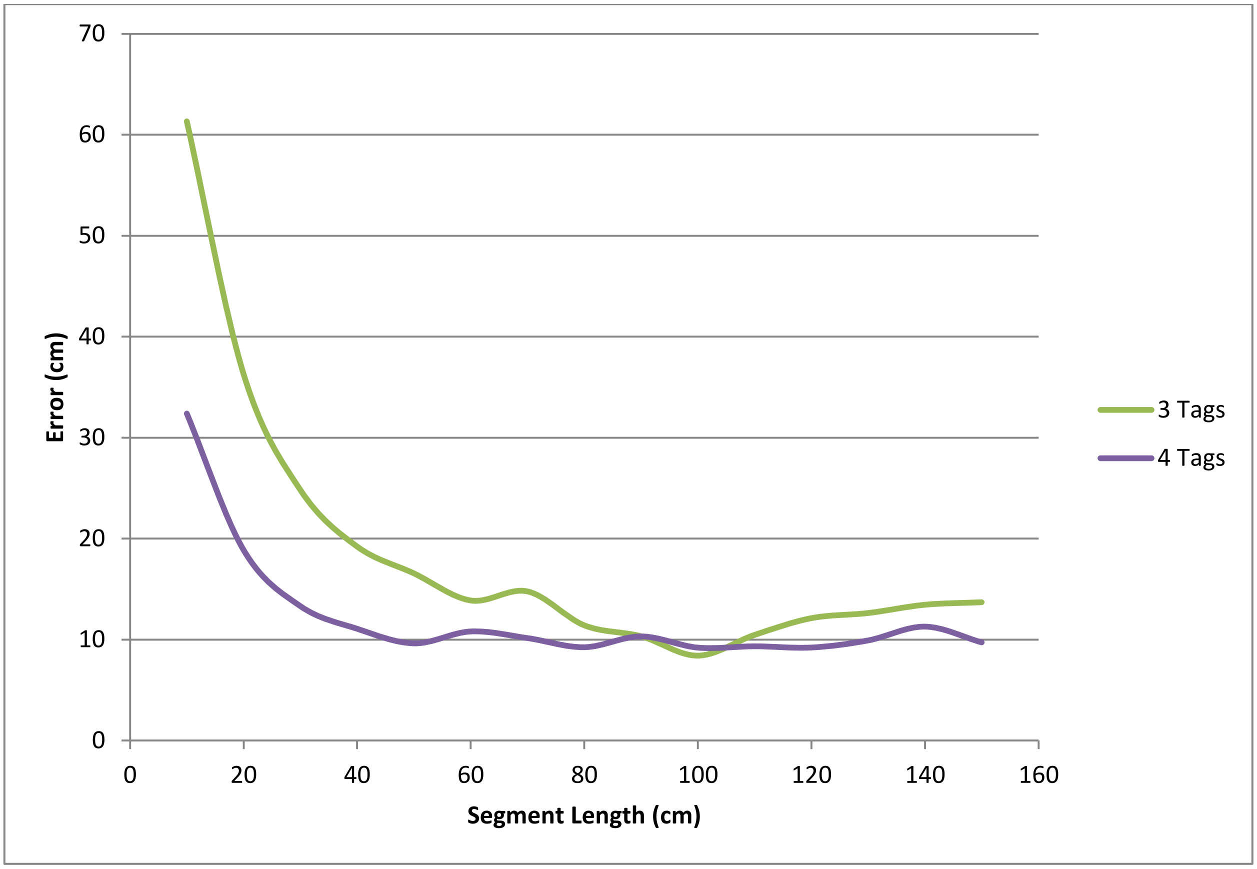

Figure 12.Error (cm) vs. Segment length (cm) for different tag configurations

The figure above clearly shows that the size of the inner tag spacing plays a great role in localization. It is also clear from the above that we have an optimal location, "sweet spot", for every number of tags. The best performance is achieved while using 4 tags with inner element spacing from 50 to100 cm. The second best is 3 tags with inner element spacing 90 cm. The logic would imply that as the number of tags increase error would decrease. However, in most cases our algorithm was unable to find a match for 6 tags and 5 tags when the area covered was increased. When a no match was found the system was penalized by adding a random error based on randomly selecting a point and considering it as a solution. The most critical point behind using 6 tags to locate the target was the amount of time taken to determine a solution if any was found. The 5 tags should have performed better than we have documented and requires additional work to be done to determine if the configuration used played a role in the performance.

4.2 Number of triangles versus Error

For small area coverage the 6 tags perform well but when the area covered increases the variation experienced by tags could not be solved. In order to further improve the accuracy we decided to divide the 6 tags into smaller 3 tag system resulting in 20 possible solutions. Solving the localization problem for three tags is very efficient time wise and will result in a solution for all attempts. The system will then use the solution of all those three tags system and use a simple average to determine its location. The results were unpredictable and relied heavily on the triangles used and the number of triangles included in the solution.

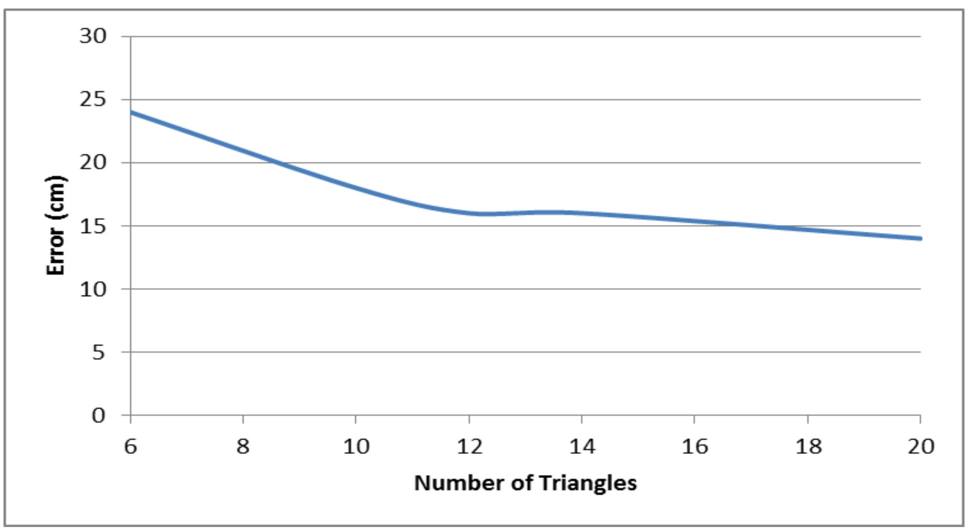

Figure 13.Error (cm) vs. Number of triangles used in 6 tag configuration

Figure 13 clearly shows that the performance will be enhanced as the number of triangles used is increased. However, the increase is not substantial and comes at great delay and cost in computation.

4.3Noise versus Error

RSSI is heavily affected by the presence of noise inside the system. We have studied the impact of noise on the accuracy of localizing using different number of tags. The results are documented below. The simulation was conducted using the best inner tag spacing for each set with a sampling space of 10 for each reading.

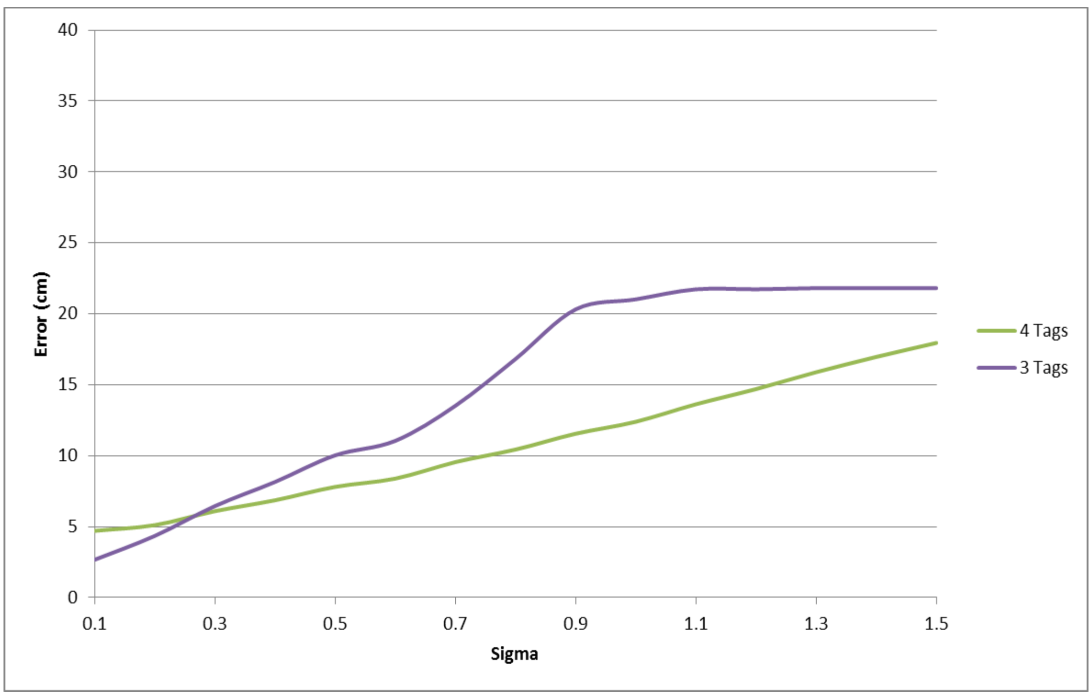

Figure 14.Error (cm) vs. Sigma for different tag configurations

The figure above shows how dependent is the localization error on sigma. Sigma is the standard deviation for the noise simulated in the environment. The increase in the noise level leads to a huge increase in error. The 4 tags will outperform 3 tags as the noise in the system is increased.

4.4Number of Samples versus Error

The next goal was to study the effect of oversampling on the localization error. The system would measure *k* RSSI values and use their mean as the received power. The graph below shows *k* vs. Error using 3 tags; however, optimal spacing was not included as a factor into this simulation. The inner tag space used was 180 cm. The height of 180 cm was determined to reduce multipath effect.

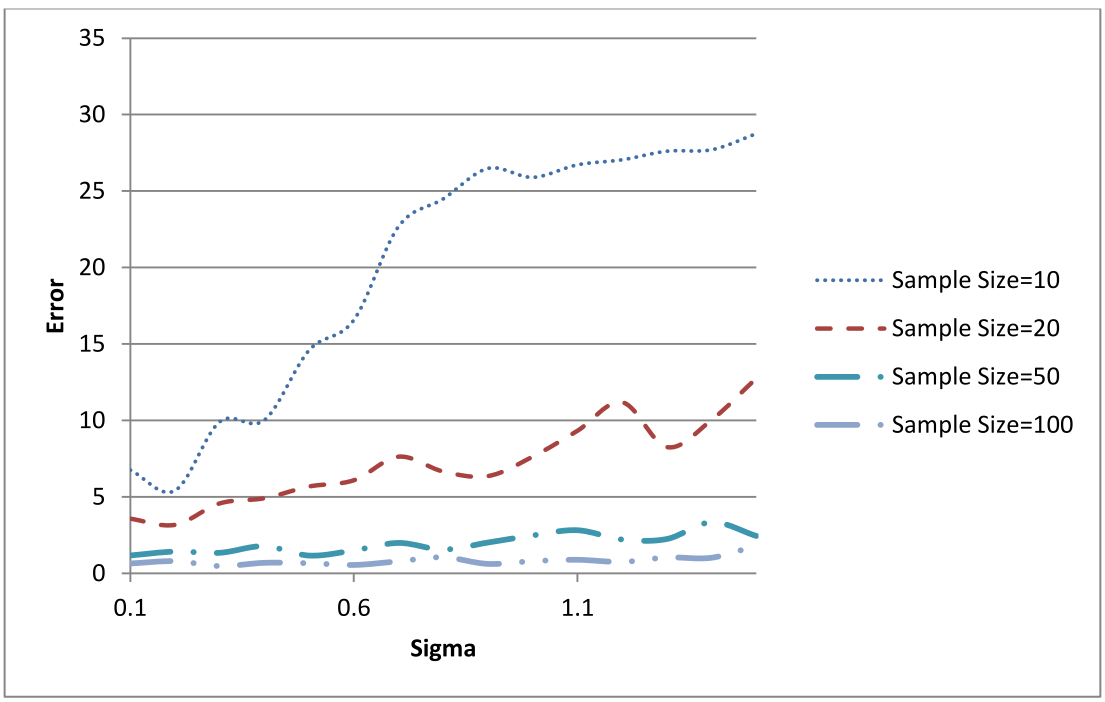

Figure 15.Error (cm) vs. Sigma for different sample sizes

The graph shows that as the number of samples increases the error decreases and approaches the Quantizing error. It is also clear that a sample size of 50 gives the same error as using a100 samples. The graph also shows that noise plays a fundamental role in the localizing error. We can state that using 50 samples will significantly reduce, if not completely remove the noise effect.

4.6 Conclusion

Based on the results shown above we can now design an experiment that should allow us to obtain optimal results. The lookup table will use a Q calculated based on our Quantizing error estimation. The information also suggests that the use of 4 perpendicular tags with spacing of about 50 cm is the best configuration to be used in our experimental results.

Chapter 5

Experimental Results

This chapter will describe the experiments undertaken to prove our concept. The experimental setup and procedure will be explained. We will then compare experimental and simulated results. The results will be presented in a tabular forum. Finally we will conclude with a comparison between experimental data and simulated real life environment.

5.1 Experimental Setup

The antenna we have used has a gain of 12 dBi and the transmitter output power is set to 30 dBm. The frequency selected is 867 MHz

We have conducted these experiments attempting to prove our experimental results. The first experiments were conducted using 1, 2, 3 and 4 tags. The tags were placed at 1.8 meter height and distance varied from 230 to 512 cm. The distances were determined by the antenna's farfield point and the reader's sensitivity. The next step was to determine how sparse are the points sampled.

Table 2 Equipment Utilized

Reader	Operating Frequencies	865-956 MHz
	RF Power	+30dBm
	Operating Temperature	-20 to 55 degCelsius

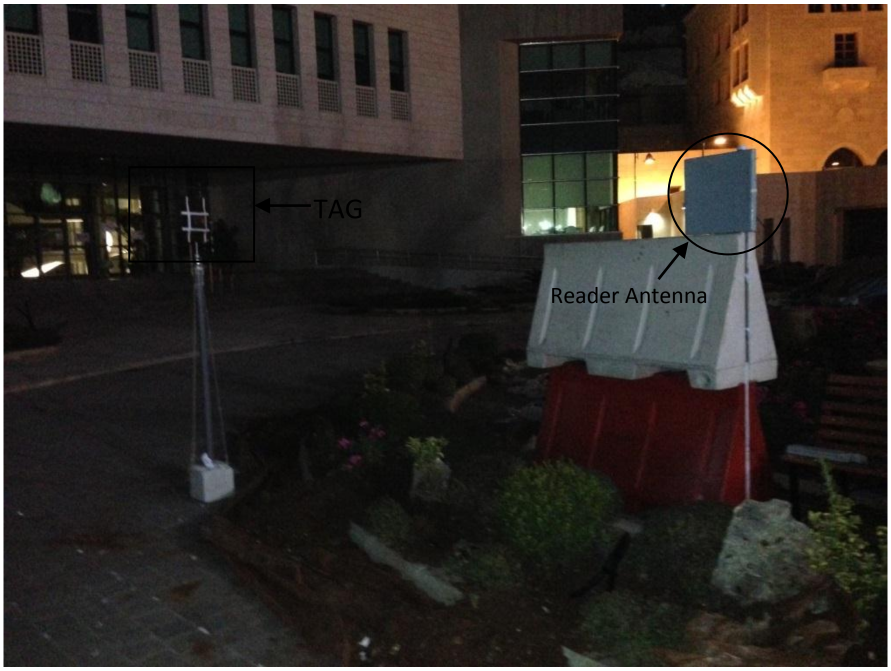

Figure 16. Reader and Tag setup

Figure 17. Grid Layout

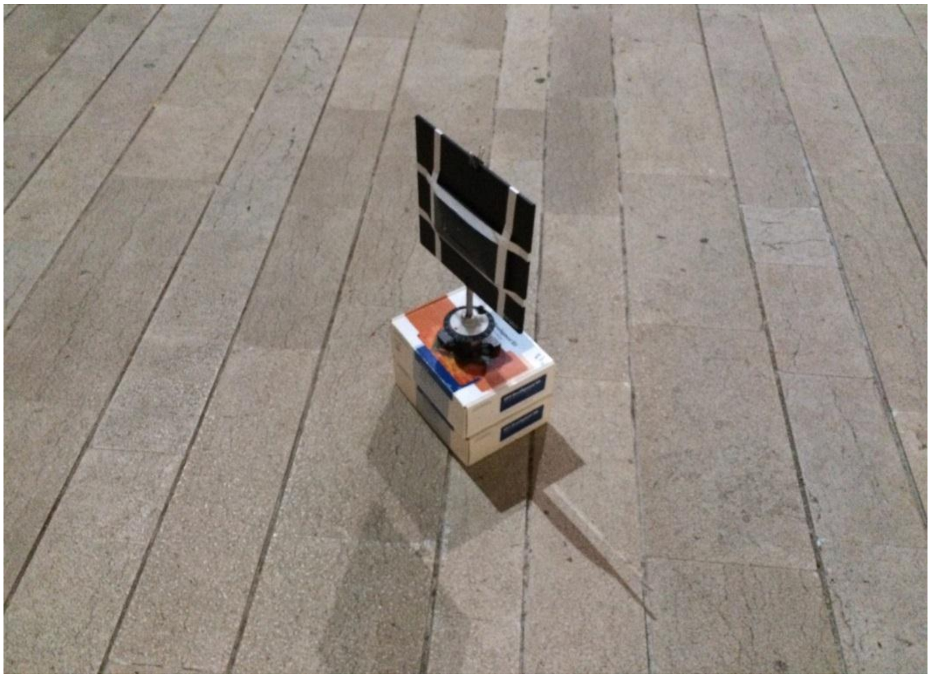

Figure 18. Tag Angle Dial

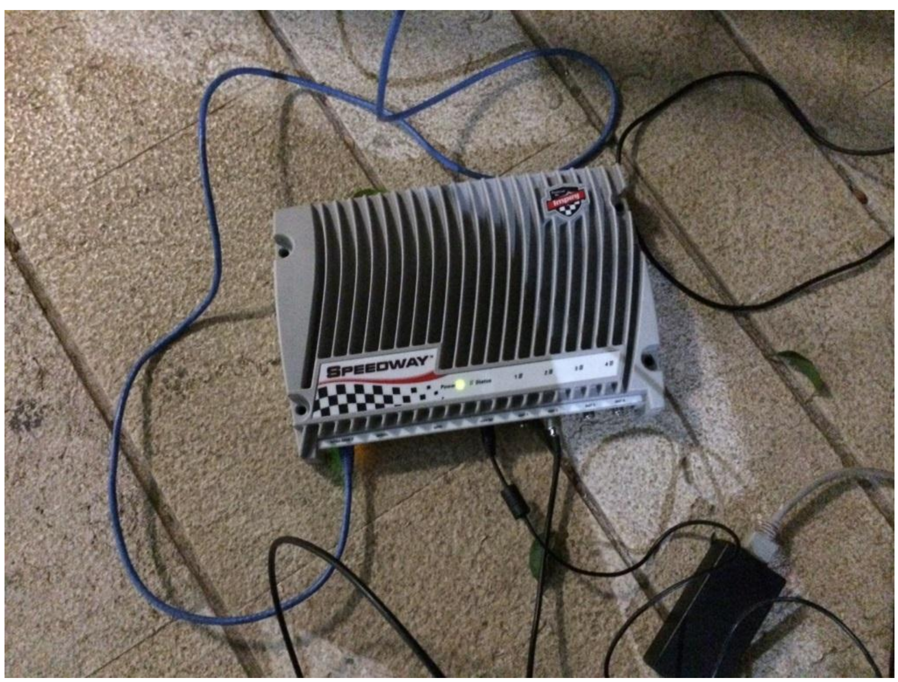

Figure 19.Impinj Speedway reader.

Figure 20. Reader’s Antenna

We measured the RSSI on 8 different collinear points at an angle of 0 with main radiation pattern. The results for the collinear points are shown below.

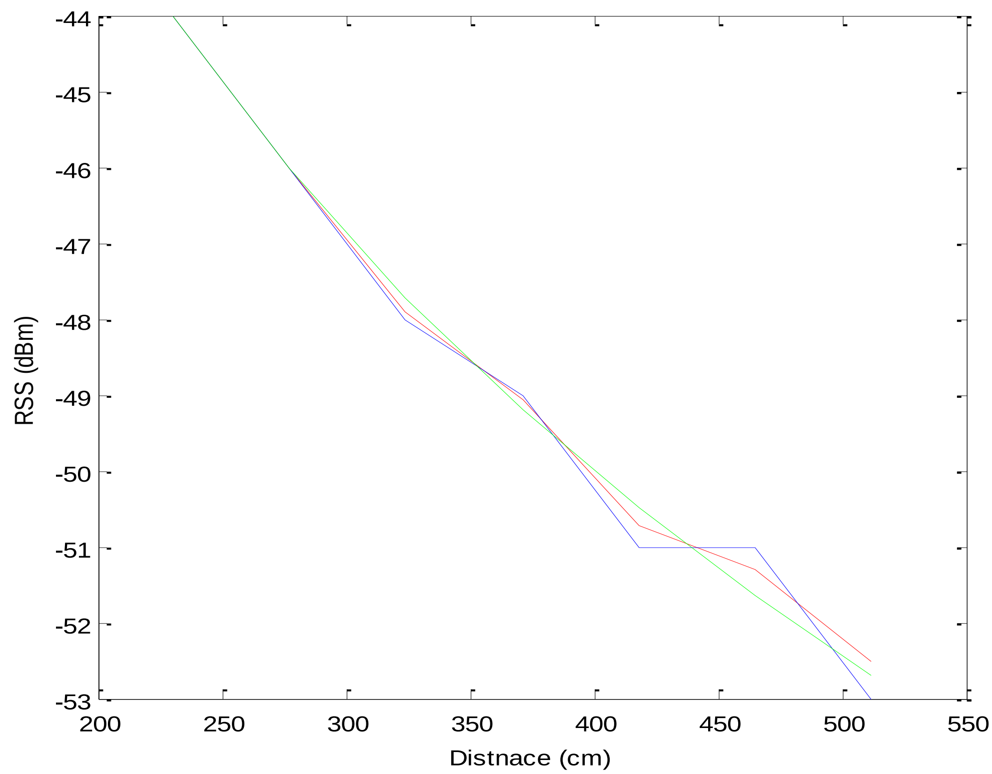

Figure 21.Power Measured, Averaged and simulated vs. Distance

Figure 21 shows the power received from a single tag measured, averaged and simulated. The graph clearly shows that as the distance increases the error between simulated and measured starts to increase. The averaging employed to reduce the power quantizing error does not significantly alter the results. That being said it does improve the performance slightly.

The received power were then used to calculate the loss factor n=2.5 inside our sampled space. Using the information about the readers range, maximum distance and loss factor we were able to calculate the minimum error to be obtained due to Quantizing error by reader and lookup table, equation (3.17).

$$1 - 10^{-\frac{k\Delta P}{10n}} \leq \frac{2E_{MQ}}{d_{max}}$$

Using Equation (3.17) provided in chapter 3 we were able to calculate our Error to be 11.5 cm. We used k=1 for best performance. The use of k=1 will result in minimum E_{MQ}. The tag's spacing was determined to be larger than 23 cm. We chose to use 46 cm as our tag spacing to give our reader the best chance at properly detecting the tags.

5.2Results

The experiment used 1, 2, 3 and 4 tags placed 46 cm apart. The tags distance from receiver was varied from 230 cm to 512 cm and angle varying from 0 to 50 degrees. In order to try and reduce the Quantizing error due to the reader's resolution; we sampled for 1 second in order to minimize E_{PQ}.

In order to test the accuracy of the lookup table we compared the simulated and measured power at locations shown in table 3. Using a single tag we sampled several points in space and recorded theRSS values. The lookup table was updated with a single reading from the environment. The power differences between simulated and actual are shown below.

Table 3.Power difference (dB) for simulated vs. measured

Deviation from main Beam (cm)						
Distance (cm)		0	47	94	141	188
	230	0	0.33	1.3477	2.1694	3.5784

	277	0.1	0.3188	1.3099	1.4897	3.0349
	324	0.23	0.2426	1.0347	1.4090	2.2588
	371	0.213	0.205	0.4336	1.4172	1.3034
	418	0.2172	0.1241	0.6715	1.2075	1.268

Table 3 shows a variation power difference variation from 0 dB to 3.5 dB. It is clear from the table that 80% percent of the measured values are within 1.5dB of predicted power. The error tabulated above is ascribed to environmental and system errors. The results prove that the use of a simulator to map the environment is a valid assumption and would behave as well as real life power mapping. The results for a single tag are shown in the table below.

Table 4.Error (cm) in localization using a single tag

Deviation from main Beam (cm)						
		0	47	94	141	188
Distance (cm)	230	0	192	241	102	109
	277	278	188	205	94	172
	324	256	196	174	109	136
	371	241	214	151	139	72
	418	235	240	141	176	48

Table 4 shows that the minimum error is 47 cm and maximum error of 306 cm. The use of a single tag yielded significant error with mean = 200 cm. The use of a single tag was able to find a match for all points tested. The errors resulting from the use of a single tag are very large. As a result the use of a single tag to localize is an inefficient effort. Using a single tag would force the system to rely solemnly on the RSSI. RSSI is highly dependent on environment and hence no two readings are identical. This fact forces the system to make an educated guess guided by received power on the tags location which in most cases is highly inaccurate. We introduced a measure of error to compare between different tables. Measure Error (ME_q) is the norm of the error matrix while q is the number of tags used to create that table. From table 4 we can write ME_1 = 34.16 cm.

The second experiment was conducted using two identical tags and for comparison the same points were chosen as before. The tags were placed 46 cm apart. The results are tabulate in the table below.

Table 5.Error (cm) in localization using two tags

	Deviation from main Beam (cm)					
Distance (cm)		0	47	94	141	188
	230	0	192	109	94	86
	277	109	188	180	94	206
	324	103	150	174	109	147
	371	137	176	151	139	105
	418	67	130	141	176	97

Table 5 shows the experimental results obtained by using two tags. The error varied from 86 to 248 cm. The use of two tags has a 90 % improvement over the use of a single tag. The error received is still significantly large and cannot be used in localization. The value obtained for ME_2 = 26.92 cm. The drop in *ME* is an indicator on the improvemed performance experienced by adding an extra tag.

The third experiment was conducted using three tags placed in a right angle triangle with 46 cm sides and 65 cm hypotenuse. The same points were chosen as before for consistency.

Table 6.Error (cm) in localization using three tags

	Deviation from main Beam (cm)					
Distance (cm)		0	47	94	141	188
	230	0	63	78	63	81
	277	20	88	97	110	94

	324	80	76	74	78	275
	371	63	79	87	59	35
	418	52	30	33	33	78

The table above shows a clear and significant improvement through the use of 3 tags instead of 2. The table shows that minimum error achieved is 12 and maximum 275 cm. The mean error is 80 cm. Though the 80 cm is a significant improvement it is still too large to be used as for localization. We calculated ME_3 to be 16.48 cm. Once more with the addition of a tag the error has decreased.

The fourth experiment consisted of the use of 4 tags. The 4 tags were placed in a square with sides 46 cm each. The square was then sampled in the same locations as before for comparison. The results obtained are shown below.

Table 7.Error (cm) in localization using four tags

Deviation from main Beam (cm)						
Distance (cm)		0	47	94	141	188
	230	0	0.34	17	35	NM
	277	0.26	12	17	17	59
	324	0.39	12	17	26	59
	371	12	12	12	17	59
	418	12	12	0.44	33	33

Table7 shows the results obtained by the use of 4 tags for localization. The results show that the mean for using 4 tags for localization is 46 cm. The results also show that for larger angles and distances larger than 512 cm the error increases. The error is increasing at larger angles due to the antenna being highly directive with gain of 12 dBi. The power delivered to the antenna at larger angels is significantly less. The drop in delivered power to tag would lead to a lower RSSI and making it more susceptible to noise and false readings. This had a significant impact on the schemes ability to localize the larger distances and angels. Our proposed system is to be used for distances smaller than 418 cm and angles below 40 degrees. We can clearly see that the points with errors exceeding 26 cm are beyond our desired region. The ME_4 was calculated without the last column to be 1.388 cm. *ME* variation shown above is a clear indicator that the use of more tags can allow for better localization without addition hardware.

Based on the above we can confidently claim that the mean error is around 15 cm. This resultmirrors our model prediction of error being around 11.5 cm with our current reader and environment.

Table 5 also introduces a new parameter labeled NM. The use of NM refers to a location where the reader is unable to locate a match. The use of 4 tags has improved the localization by 90% and dropped the mean error from 80 cm to 15 cm.

In order to further verify the match between our simulated and measured results we designed a new simulation. The simulator would take the measured parameters for sigma and *n* based on that a lookup table was generated as we did with actual measurements. The next step was to simulate the behavior of the tag at the exact point we have samples. The results are provided below.

Table 8Error (cm) in localization using four tags simulated

	Deviation from main Beam (cm)					
Distance (cm)		0	47	94	141	188
	230	0	1	5.6	5.6	1
	277	1	5.4	2.1	2.1	4
	324	2.9	2.1	3.5	14.2	2.1
	371	1.9	2.1	4.1	2.7	2.1
	418	4.9	10.4	3	6.4	6.1

The simulator was fed the same locations and parameters as the real life measurements. The simulator was allowed to make 100 samples per reading. The simulator matched to a great extent the values observed in real life. The error pattern is similar. The *ME* was calculated to be 0.88 cm. The differences in measured error observed are due to power quantizing error by the reader which has not been introduced into our simulator.

The reader has a sensitivity which makes it susceptible to noise when RSSI decreases beyond certain threshold. The simulator has no such limitations. This results in a variation while using angles and distances beyond our reader's capabilities.

To more accurately compare the results obtained from experimental work and simulated results new parameter was added. The new parameter is characterized by addition of power quantizing error in the simulation. The simulator was updated to round RSS. The new values were feed into the solver. The results are documented below.

Table 9.Error (cm) in localization using four tags simulated with power quantizing error

Deviation from main Beam (cm)						
Distance (cm)		0	47	94	141	188
	230	0	5	7	6	9
	277	1	7	2	3	6
	324	6	2	8	16	3
	371	2	3	8	4	3
	418	8	14	5	2	7
	465	18	1	9	6	10

Table 9 shows that the error has increased. The new measured *ME* is 1.4. The increase in *ME* is due to power quantizing error. This is an indicator that the difference between measured result errors and simulated is due to the power quantization error, other factors might have exacerbated the error due to power quantization.

5.3 Conclusion

We have tested our localization scheme in a real world application. The proposed system can deliver a performance of 15 cm and standard variation of 4 cm accuracy. The scheme behaved as simulated. The error achieved has been predicted by Quantization error formula developed in chapter 3. The performance deteriorates significantly and became less predictable for larger angles and distances due to our reader's sensitivity and limited range. The experiments have proven the dependency of localization accuracy on number of tags used. The use of 4 tags has outperformed the use of 3 or 2 tags.

Chapter 6

Conclusion and Future work

6.1 Summary

The concept of a single stationary antenna with multiple tags on asset was justified. The scheme proposed did not require the sample space to be pre-sampled for the creation of the lookup table. The proposed scheme relies on antenna radiation pattern and a single point entry to generate the power lookup tables. This feature makes it extremely robust and mobile since no extensive calibration is required.

We have explored multiple aspects to improve accuracy. First, we proved our concept numerically by simulating the effect of multiple tags on localization accuracy. The use of multiple tags proved advantageous in numerical result. In order to corroborate the information construed from simulation, several experiments were conducted. The experiments were conducted in same environmental conditions. The same points were used in simulation and experimental setup for comparison. The experimental data consolidated that accuracy increases with number of tags used. The introduction of more tags allowed for better filtering allowing us to refine the location to minimize the error. The experiment also showed that though the increase allows for better accuracy, larger and larger numbers of tags would impose too many constraints on our filtering rendering it impossible for the software to find a point to match all of the requirements. The experiments concluded the spacing between tags has to be predetermined based on environment and reader used. The use of smaller spacing would render the scheme inaccurate due to power quantizing error. We were able to achieve 15 cm accuracy by the use of 4 tags with 36 cm spacing.

6.2 Future Work

The experiments and simulation conducted during this study led to new research areas.

1. First, relation between inner tag spacing and frequency is still to be investigated.
2. Second, minimize the effect of power quantizing error in a reader
3. Third, update software and try using directional RFID tags
4. Repeat experiments with non-directive antenna

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