Localization and Proximity Detection in the Internet of Things Based on an Augmented UHF RFID System

by

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Abstract

In the "Internet of Things" (IoT), the things will be able to sense, communicate, and interact. They will also exchange data, information and knowledge, and locate themselves and other things that surround them. In order to be able to interact, the things need to recognize that they are in proximity of other things. It is anticipated that the most widespread components of the IoT will be passive radio frequency identification (RFID) tags because they are inexpensive and provide automatic identification. However, passive RFID tags are not capable of performing complex operations, such as proximity detection and localization, which will be required in future networks. In this thesis, we describe existing problems with current RFID systems and survey potential solutions for localization and proximity detection. Then we present a new RFID device called "Sense-a-Tag" (ST) that can passively detect and decode backscattered signals from tags in its proximity. There have already been an attempt to use this device for tracking. However, detailed analysis of the performance of the ST especially for proximity detection has not been performed yet. We show that when STs are added to a standard RFID system, the problems of proximity detection and localization with RFID tags can readily be solved. Then we applied ST-based system for identifying people and object interactions. The potential uses of ST as an augmented device for IoT applications are discussed in this thesis. Advantages and limitations of an ST based RFID system have been investigated in details for each application.

Results obtained from real experiments illustrate that an ST-based RFID system is feasible for proximity detection applications. In addition, a special software is developed in C# to process the data and run a localization algorithm based on proximity detection information. The same software has been used for tracking people's activity. Different scenarios have been considered in the experiments. We tried to consider majority of factors that might affect the accuracy in the experiments including: angle and distance between the reader/ST and tags, timing in sending queries, presence of human body, etc. The simulations based on real experiments and results illustrates that an ST-based RFID system can be a realistic solution for proximity detection and localization for Location Positioning systems (LPS) and activity monitoring in future IoT.

Acknowledgements

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Last, but not least, my family for always believing in me and always encouraging me on every step of the way.

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List of Abbreviations

3D 3 Dimensional, page 3

AOA Angle Of Arrival, page 3

ARR Augmented RFID Reader, page 5

CL Centroid Localization, page 71

DOA Direction of Arrival, page 22

EPC Electronic Product Code, page 2

FFC Far Field Communication, page 14

Gen2 Generation 2, page 2

GPS Global Positioning System, page 2

HAN Home Area Networks, page 9

IoT Internet of Things, page 3

IP Internet Protocol, page 11

IPS Indoor Positioning Systems, page 21

IR Infra Red, page 3

Kb Kilo Byte, page 15

LLRP Low-Level Reader Protocol, page 69

LOS Line Of Sight, page 2

NFC Near Field Communication, page 13

OCR Optical Character Recognition, page 11

PDoA Phase Difference of Arrival, page 22

RFID Radio Frequency Identification, page 1

RSS Received Signal Strength, page 22

RTLS Real Time Localization Systems, page 2

SoC System on Chip, page 11

ST Sense-a-Tag, page 3

TDoA Time Difference of Arrival, page 22

ToA Time of Arrival, page 22

TOF Time of Flight, page 18

UHF Ultra High Frequency, page 14

UWB Ultra Wide Band, page 23

WCL Weighted Centroid Localization, page 72

WLAN Wireless Local Area Network, page 23

Chapter 1

Introduction

1.1 Overview of the field

1.1.1 RFID System

RFID is a wireless data transmission process between an interrogator called a reader and a transponder called a tag. The tag consists of an internal memory or one/multiple sensor(s) that send information to the reader. The reader is usually connected to a host computer with a database, in order to do further processing of information received from the tags. Currently, RFID technology has been applied to many applications such as transportation, asset management, logistics, animal tracking, supply chain, etc.[6]

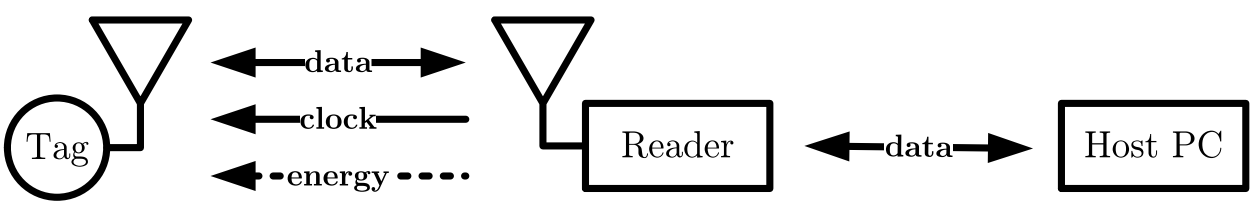


Figure 1.1: High-level block diagram of RFID system

RFID systems have different categories based on frequency and working mechanism.Tags are clasified as active, passive and semi-passive. Majority of active tags include a power source and send their information toward a reader at preset intervals. Commonly, passive and semi-passive tags send their information when they are activated by the signal from the reader. Both passive and semi-passive tags transmit the data by backscattering the reader's signal. The main difference between passive and semi-passive tags is that semi-passive tags use internal battery for their internal process such as decoding signal or reading sensors, and increase the sensitivity and read range by this way. RFID systems operating in KHz, MHz and GHz have different applications and standards.

1.1.2 Passive UHF RFID

Passive RFID has been introduced as a replacement for barcode systems. Originally, they were designed for the identification of small goods. Passive tags are inexpensive and come with memory and the ability to modify memory. Some passive tags also integrate authentication and encryption. These features open doors to other applications too [7].

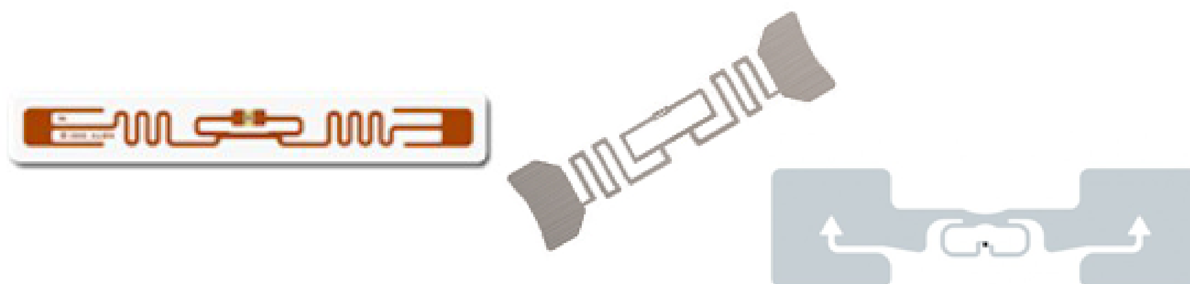


Figure 1.2: Commercial UHF RFID tags

EPCglobal Class-1 Gen2 (ISO 18006c, [8]) UHF RFID is a "reader talk first" protocol for passive UHF RFID systems. The tag waits to be addressed first. Then it transmits the data using backscattering modulation, which can be its identification code or parts of its memory.

1.1.3 Real Time Localization System (RTLS)

Since satellite based navigation techniques such as Global Positioning System (GPS) are limited to outdoor areas, and wireless network devices are large and expensive, indoor Real Time Localization Systems (RTLS) are an emerging application of RFID systems. Non RF-Based localization techniques like laser-based, infrared and ultrasonic localization are affected by environmental impacts such as fluorescent lights. They are limited to applications that can satisfy Line-of-Sight (LOS) readability. One of the main issues with RF-based systems is multipath propagation. Some approaches have been introduced to estimate distance between unknown targets and known ones such as readers. Received Signal Strength Indication (RSSI), Time of Arrival (TOA), and Angle of Arrival (AOA) are the most well-known. The problem with all of these techniques is that in reality using backscattering modulation does not follow the theoretical propagation model. The better solution to localize is proximity detection, by using intersection of several coverage areas. We should note that proximity techniques are dependent on the density of reference tags and reader distribution which increases their cost. Most of the reported RFID-RTLS systems are still designed for two dimensional space and there is not much research yet on 3D systems.

1.1.4 Proximity Detection

Proximity detection systems can detect the presence of an object or person. In proximity detection, the actual locations of the two objects are not important. The only important factor is the presence of two objects near each other. Proximity detection systems became more popular when the Internet of Things appeared. With the IoT, there has been a need to recognize objects or persons in each other's vicinity in situations like mines, work areas, medical care and social interaction. Depending on the application many different technologies such as such as IR sensors, Sonar sensors, GPS, RFID, etc. have been used to detect proximity[9].

1.2 Problem statement

In recent years the concept of the Internet of Things (IoT) has been gaining popularity. The basic premise of the concept is that "things" are interconnected and have unique identifiers. With such technology implemented, waste products and inventory mismanagement will be a thing of the past. One of the potential technologies for the IoT is RFID. The coarse-grained knowledge of the location of a tag offered by RFID systems is not suitable for the context-awareness of identifiable objects in IoT. The objective of this thesis is to analyze and improve the functionality of a novel semi-passive tag called "Sense-a-Tag (ST)" introduced in [10]. The ST can overcome the existing limitations of RFID systems including cost and performance. The existing systems for proximity detection and localization, are based on active systems and run on specialized platforms. Since ST can be added as a new hardware to any current RFID system without any modification in hardware or firmware, it can be considered a realistic solution for proximity detection and localization applications. In this thesis we show how ST can be used for tracking, localization, proximity detection and people interaction monitoring. The method described in this thesis, overcomes the limitation of existing RFID localization systems including cost, accuracy and scalability. This new method has many applications using UHF RFID for the IoT.

1.3 Motivation

The motivation behind this thesis to open new doors for using RFID systems in multi-purpose applications. Nowadays, RFID readers and tags exist everywhere. RFID systems have only been used to recognize and identify items. However, these wireless systems are capable of much more.

Since the epiphany of the IoT, RFID has became more popular and is being explored for use in developing IoT technology. Three key answers to who?/where?/when? can cover all the needs of many smart applications. Today, current RFID system can answer some of these questions. However, estimating the location of objects using RFID is still challenging. Interaction between the objects and people can provide valuable information that can be used for different applications such as marketing and health monitoring. ST, as an augmented device, has been added to RFID system to increase its capabilities. Although tracking has been introduced as one of the applications of ST, detailed analysis of performance of the ST-based RFID system especially for proximity detection application has not been performed yet.

We investigated the *"weighted-centroid"* method of localization and activity tracking system based on proximity detection using ST and RFID passive tags.

1.4 Objectives

Passive RFID tags are expected to be the heart of the IoT because they are inexpensive and they do not need internal or external power source. However, passive RFID systems are not capable of performing complex operations such as proximity detection and accurate localization, which are important to the IoT. There are three different scenarios for the object location information using RFID systems:

- Localization of stationary objects.
- Localization of moving objects tagged with RFID tags.

- Detecting proximity between objects.

In the past decade much research has been done on using UHF RFID for proximity detection and localization. Gen2 listener [11], Augmented RFID Reader (ARR) [12] and Tag-to-Tag communication system [13] can be counted as similar works to ST. But none of these researches have been able to offer low cost, mobility and precision.

The main objective of this thesis to investigate the performance of an ST-based RFID system for localization and proximity detection application while keeping the overall cost of RFID system low and by reducing mobility of tagged objects in the RFID system.

1.5 Contribution

Required localization accuracy of the system is different depending on the applications. For indoor localization, less than 25cm accuracy can meet most of the application's requirement. For proximity detection, required detection rate is 90%. The method introduced in this thesis offers a less expensive proximity detection system than similar efforts such as Gen2 listener [11], Augmented RFID Reader (ARR) [12] and Tag-to-Tag communication system [13]. It also offers good accuracy to be used in many applications. The contribution of this thesis can be summarized:

- Development of a real-time and multi-threaded software to localize tagged objects.
- Development of a real-time simulator based on real results for proximity detection.
- Measurement of the performance of ST with passive and semi-passive tags in real environment.
- Demonstration of the proximity detection of ST as a people interaction detector system.
- Investigation of ST potentials in IoT applications based on proximity detection.

1.6 Thesis Organization

Chapter 2 presents a background and literature review on the RFID system, Internet of things (IoT), realtime localization systems(RTLS) and proximity detection, with emphasis on the UHF RFID-EPCGen 2 standard.

Chapter 3 presents the description of ST including its functionality and potentials for proximity detection and localization. A survey about similar devices that augment the RFID systems is presented in this chapter.

Chapter 4 describe how ST can be a helpful device for future IoT. We summarize the problems with regular RFID system and show how some of those problem will be solved in ST-based RFID system. Advantages and limitation of ST compared to other solutions in proximity detection have been discussed in this chapter.

Chapter 5 summarize a experimental analysis for basic tests in ST-based RFID system. We describe the proposed localization and proximity detection system designs, in the real environment and investigate the parameters which might affect the read-range and accuracy.

Chapter 6 covers the experimental results and analysis for the experiments that have been done based on some IoT applications. Different factors that affect the localization and proximity detection discussed in this chapter. Also the accuracy and reliability of the system have been investigated for each application.

Chapter 7 summarizes the conclusions and recommends future research.

Chapter 2

Background and Prior Art

2.1 The Internet of Things

2.1.1 Overview

With the daily development of technology and ever increasing connections between hardware and software, society is moving towards the concept of "always being in touch". Nowadays, networks exist everywhere, either wired or wireless. This has led to proposals for new networks where objects and people are connected over the internet known as "Internet of Things". Many researchers believe that the IoT will change the world for people and objects in the same way that the internet did for the information [14]. The usual path for developing a product is to start from science and end in engineering. But the IoT is an exception[15]. Because engineers came up with the idea of IoT after wide-spread use of RFID in different applications.

2.1.2 IoT Architectures

The architecture of the IoT consists of three main layers: perception, network and application [16]. Later, researchers proposed a more layered architecture that consists of perception, transport, processing, application and business [17]. The perception layer gathers the data and information by various data collection technologies such as barcode, RFID, camera, sensors and etc. The transport layer is responsible for transmitting data received from the perception layer. Protocols for communication such as IPV6 are applied in this layer. The processing layer stores, analyzes and processes the information about objects received from the transport layer. The application layer addresses industry and society demands and the search for solutions to them. Finally, the business layer, acts as a manager of the IoT, finding a business model for new applications.

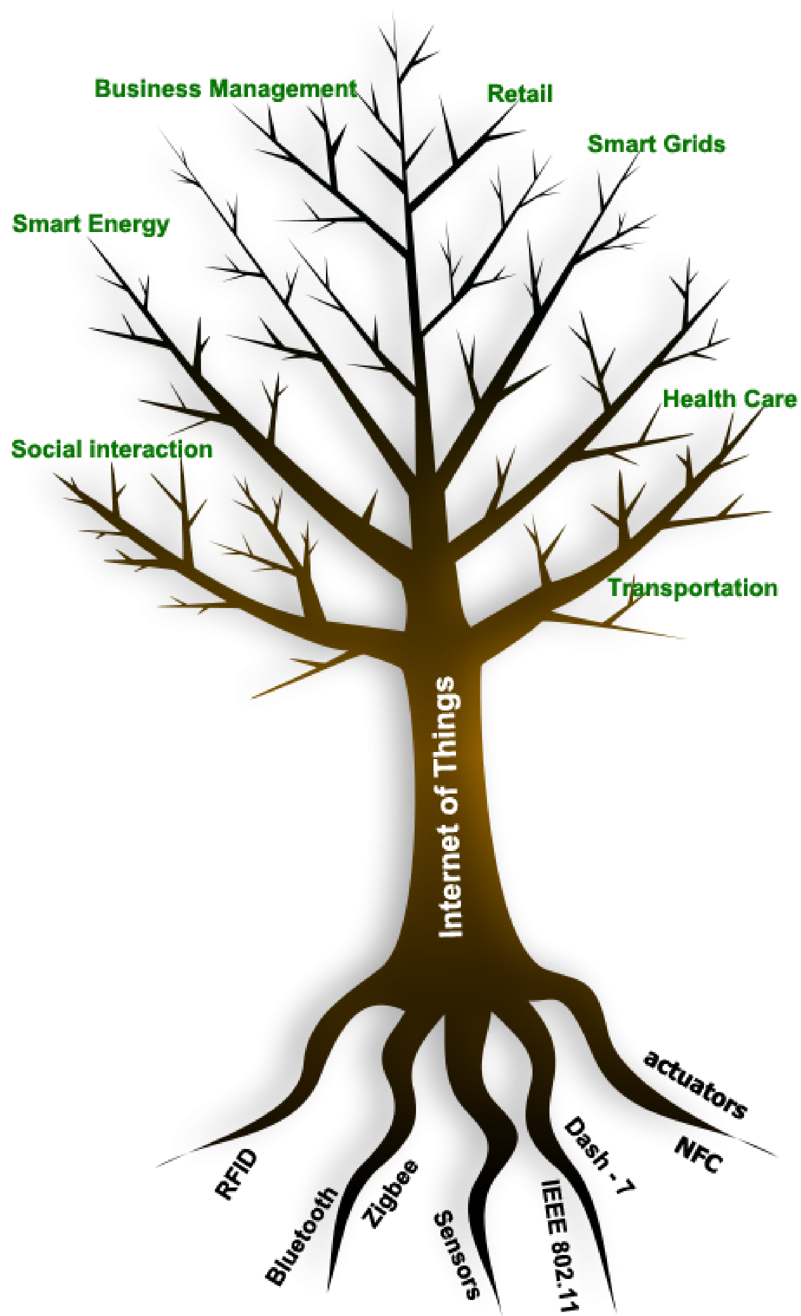


Figure 2.1: Internet of Things concept

2.1.3 IoT Requirements

Bill of material(BOM) cost

Internet connection price is one of the issues in the globalization of the IoT. Connecting to the internet requires widespread memory and CPU resources. These are needed to support heavy weight TCP/IP protocol and operating systems to communicate over SSL. This increases the cost of the system. Some home area networks (HAN) have been developed to be able to communicate with small packet sizes such as ZigBee, Z-Wave, RFID, etc.[18], But these technologies are not designed for global usage. It is impossible to carry HAN protocols over the internet. So we need a convert the protocol on the first gateway so that it can be carried over the internet. To solve this problem, XML based communication technologies (e.g. REST, JSON) have been developed. The problem with them is that huge code libraries are needed[19]. The cloud computing design pattern made it possible to use 8-bit MCUs with a small amount of memory in communication infrastructure. However, RFID, as an interface between nodes and internet connectable devices, can collect the data at lower cost which enables higher production volumes.

Ease of installation

The installation process for any IoT system should be easy enough that non-technical people can use them in their environments. One of the problems in IoT applications for a regular customer, is setting up the router and assigning a special IP address to the endpoint. Another challenge is that it is not possible to define a static IP for each item in an area, so we usually use dynamic IP addresses. Cloud computing based communication schemes outside the consumer‘s firewall, somehow solved this problem. However, the easier way would be to gather the information by an interface and assign a single IP address to only one reader. RFID can help us here by collecting the data from tags and making it ready to send through the internet.

Security

Depending on the application, security is one of the most important parts of any network. For security purposes, Let us consider separately the HAN and the internet connection.There are many types of technologies to provide security for the internet. Some are expensive(e.g. SSL, VPN) and some are cheap(e.g. WPA, WPA2, etc.). For the HAN, depending on the technology that we are using, security methods can be changed. Unfortunately, UHF RFID security is not completely reliable. Although many 8-bit MCUs used in low cost end point have 128-bit AES encryption in their hardware without any extra cost, providing a secure connection in low cost design of UHF RFID tags is still a big issue.

Reliability

A basic expectation of consumers is reliability. Among the most common problems with internet connectable devices, is that they freeze up and need to be rebooted manually. These problems are frequently experienced with OS based PCs and smart-phones. We need a reliable and less vulnerable internet connection. For example, a consumer, who wants to be able to check remotely whether they have left their stove on, will not be satisfied if they cannot check because their home computer has shut down. RFID because of its simple architecture offers an alternative not vulnerable to these problems. Even if electricity is lost, RFID can boot automatically and continue the operation. Only a simple interface hardware is required here to make the information from RFID readable for WiFi routers.

Scalability

When we are talking about the IoT, we are considering millions of devices as endpoints in our network. So it is essential to pay attention to scalability. Storing the information of each endpoint in one database will be impossible. A SQL database on a server can handle maximum 1000 SQL operations per second. Currently, most MCUs profit from reasonable EEPROM and FLASH memory. These memories have been integrated in UHF RFID tag chips (e.g. NXP, Impinj, and EM Microelectronics) [20][21]. By storing information inside the tag or middle-ware, and calling them only when we need the information, we actually create millions of small databases which are always accessible.

2.1.4 IoT and RFID

RFID is the starting point of the idea of the IoT and researchers started to develop the IoT without any deep understanding of the science behind it. Nowadays, IoT is based mainly on RFID. Since each RFID tag has a unique ID, each tagged item has a unique identity in the world. Therefore, it is possible to send to and to gather information from of all the objects around us. RFID tags send their information to a reader that can include only tags' IDs or additional data such as data obtained from attached sensors. After receiving this information, the reader will send it to a host computer where further processes can be done. In both defined architectures in section 1.2, the perception layer plays the main role in the IoT. Data collection technologies such as ZigBee, RFID, NFC, Bluetooth, Z-wave and others have grown a lot in the last decade. To actualize the IoT, each object (thing) should have a unique identity in the network. This can be a unique IP or ID which can be addressed locally in the network. IPV6 protocol allows that each node in the network can have its own IP address. The same thing is true for RFID systems. RFID is one of the best solutions for data collection and meet the IoT requirements [22] mentioned above.

On the other hand, microprocessors and SoCs are getting smaller and require less power [23]. This opens up the opportunity to integrate light weight network protocols in RFID tags. Ideally, we will be able to keep the passive property of RFID systems, while allowing the tags to connect Internet through a simple interface and lightweight protocols[24].

2.2 Radio Frequency IDentification (RFID)

2.2.1 Overview

RFID technology is a wireless data collection technology that permits unique identification of objects. It is one of many types of automatic identification, including bio-metric(exp. fingerprint), Optical Character Recognition (OCR), and smart cards. In comparison with barcodes, RFID has the advantages of: longer read range, supporting larger memory and not requiring line of sight. A simple RFID system is shown in Figure2.2. A reader sends data, power, and the clock to tags. The tags respond to the commands of the reader using the backscattering technique.

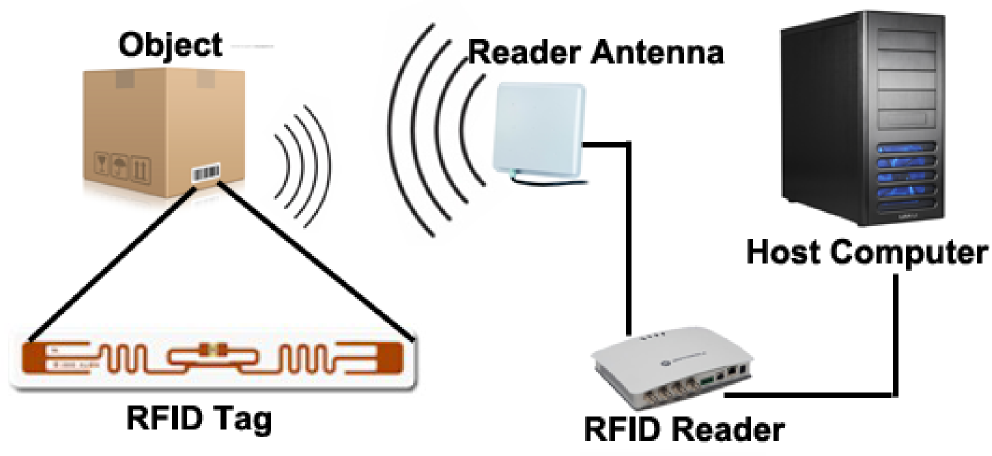


Figure 2.2: RFID System

2.2.2 RFID Classification

RFID systems are classified based on either their frequency of operation or power system. In some references [25], researchers classified the RFID systems based on coupling method.

- Frequency

The first type of classification for RFID systems is their frequency of operation. Depending on the frequency range, the applications are also different. LF systems profit from a high penetration rate that allows them to be used near metal or water. HF systems have a longer read range and also are much cheaper than LF tags. Finally UHF tags have highest the data rate, the longest range and the lowest cost compared to the others. Figure 2.3 shows different frequencies that RFID systems can operate in.

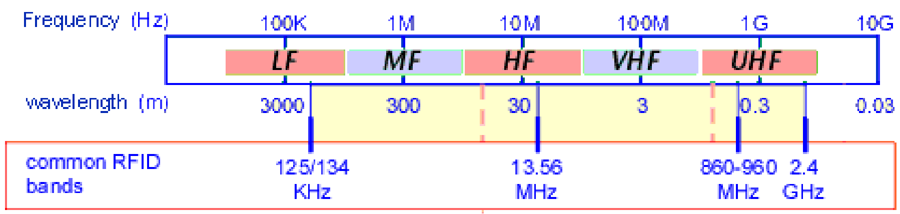


Figure 2.3: Different radio frequencies for RFID

- Power

RFID systems can also be classified according to how they get their power for operation: this can be passive, semi-passive and active. Both passive and semi-passive tag are activated by the RF signal from the reader. The passive tag is only powered by the energy transformed from the radio wave from the reader. This significantly reduces the read range for tag, but also makes it smaller and cheaper. Semi-passive tags use battery for their internal processing and to power up the sensors integrated with tag. As with passive tags, they don't use internal power for transmitting the signal. Both passive and semi-passive tags send their signal using the backscattering modulation. A backscatter RFID system is basically a radar system in which the reader (radar transceiver) provides the radio frequency signal for communications in both directions. The tag has no transmitter power generating source, but uses the incident power from the reader on which to modulate its response. Active tags use their power for all required operations. Their read range is much longer than passive and semi-passive group. Active tags are usually tag-talk-first. Since cost and life time are two major factors that make this technology so widespread, power is very important in RFID. Semi-passive tags and active tags usually have a maximum life time of 3-5 years.[26] passive tags can work in definitely unless they are physical damaged.

- Coupling

Coupling in RFID refers to the way that power is transferred from the transponder to the tag. Two types of coupling are already in use in different RFID systems: inductive (or near-field) and radiative (far-field) [25]. Near Field Communication (NFC) is a set of standards for electronic devices, communicating with each other, from not more than 10cm apart. When in proximity, the initiator actively generates an RF field and powers up a passive target. In Far Field Communication (FFC), a receiver can pick up a signal without having any effect on the original signal from the source. Tags will communicate by modulating their message on the carrier signal in passive mode, which is called backscattering modulation.

2.2.3 Reader and Tag

A RFID reader is a device that communicates with compatible RFID tags with one or multiple antennas. Modulation and demodulation are done inside the reader. Some readers can have data transmission with both active and passive tags in the same frequency, but most are only capable of working in just one mode. Database management and special reader settings such as threshold justification for power of the RF signal, are usually done by the host computer connected to the reader. A RFID tag is a device that contains internal memory and unique ID. Some tags have sensors integrated within them and can transmit the sensor information using RF signals. As mentioned before, tags can be categorized by their power type: passive, semi-passive and active. Active tags usually send their information when they receive the activator signal from the reader. Then they send their information at a specific time interval. Passive and semi passive tags are usually reader talk first systems, so they will respond to the reader using backscattering modulation.

2.3 EPC Global Standard

2.3.1 EPC Global

EPCglobal is an organization with the goal of promoting and standardizing EPC (Electronic Product Code). EPC is an RFID coding scheme, for replacing the old barcode system. EPC standard offers a large variety of fields in UHF RFID to improve its capabilities including: the capture of information, the exchange of information, and the identity of information. Figure 2.4 shows the EPCglobal standards hierarchy.

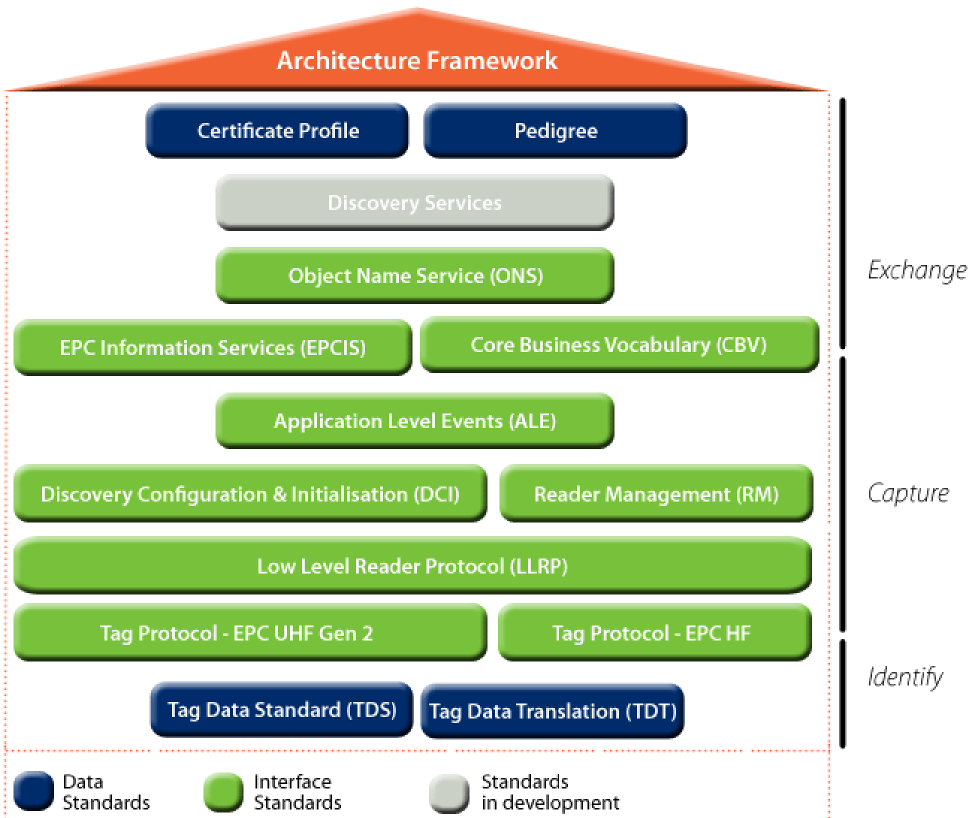


Figure 2.4: EPCglobal framework [1]

2.3.2 EPCglobal Class 1 Generation 2 Standard

The main specification of the standard is the electronic product code, Figure 2.5, which is the global identifier tags use in the EPC Gen 2 standard. The EPC has 96 bits, which identify respectively the encoding standard, company information, product type, and unique item identifier. The idea is that each tag has a unique ID. Using EPC Gen2, we can identify 268 million different companies, each with 16 million distinct object classes. That means we can have 4288 billion unique serial numbers in the world. In addition to an EPC number, tags can store information such as expiration date, manufacturing date, manufacturing location, etc. New tags can have more than 8Kb memory in the chip and can send information using the RFID interface to the reader.[20]

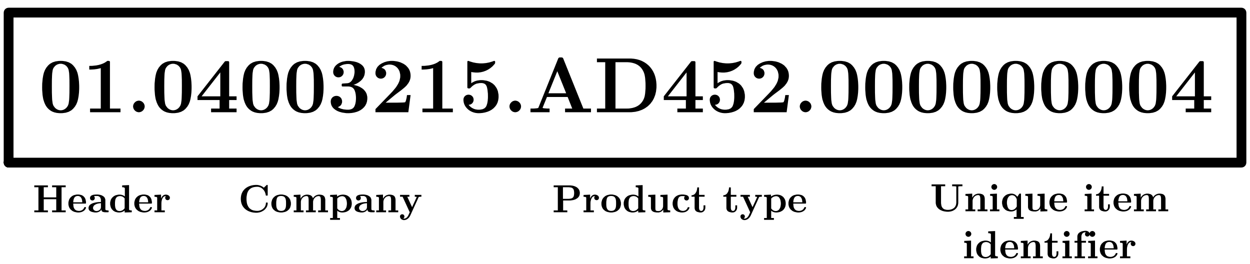


Figure 2.5: Electronic product code

2.4 Localization

2.4.1 Overview

Localization is the answer to the three main questions in many applications: What/Where/When?. Location information can be reported using different technologies. Satellite based navigation techniques have been studied well in recent decades. But they are limited to outdoor localization and cannot be used in the indoor environments. Generally, we can divide positioning systems to two main categories: RF-based and non RF-based. The main advantage of RF-based in comparison with non RF-based such as ultrasonic, infrared (IR) and laser localization, is that almost all non RF-based techniques are restricted to Line-of-Sight (LOS) readability. Our focus in this thesis is on RF-based localization systems that are used indoors.

2.4.2 Range-based techniques

In range-based localization, methods are dependent on accurate ranging results that we can get from our sensor nodes. Previous designs based on this methodology such as Cricket [27], Radar [28], APS [29], PinPoint [30], TPS [31], BeepBeep [32], SpinLoc [33], etc, all required ranging results obtained by using angle, relative velocity measurement or fine-grained point-to-point distance information. After receiving this information, positioning calculations such as triangulation [34][35][28], bilateration [36], multilateration [37][38], and etc, are applied to the results to estimate the location of the sensor node. In this subsection we will explain range-based methods based on: signal strength, time of flight and angle of arrival. Hybrid measurements would offer more accuracy and system flexibility[33][39]. However, this classification is only based on fundamental methods.

2.4.2.1 Signal Strength

Received Signal Strength (RSS) can be measured at almost no additional cost to the system, so it became the most popular method for range estimation in many wireless networks. Signal strength can be reported as a part of message in the reader side. Most of RFID readers also report RSS using their interfaces such as LLRP. The problem with RSS is that it is dependent on the environment and is susceptible to reflecting changes caused by other objects in the area [40][41]. Without having a detailed model of the physical environment inferring distance from RSS will not be precise.

SpotON [42] uses signal strength and triangulation techniques using active tags for localization. Such techniques are less feasible with passive tags since they do not have any power source. That results in a weak, unreliable signal that is causes significant errors in triangulation techniques.

To improve the accuracy of positioning based on RSS, two solutions have been investigated.

- directly infer distance from RSS measurements based on statistic results and multiple measurements[43][44].
- radio profiling and radio-frequency (RF) fingerprint matching [45][46][47].

2.4.2.2 Time of Flight(TOF)

Many localization systems use time of flight measurement of radio signals to estimate the range. In this methodology the distance is calculated based on the speed of signal propagation and the time elapsed between the signal transmitter and receiver. Sometimes, in synchronized nodes, the start time is sent through the packet and the received time is replied in the return message. On the host side, based on the speed of signal propagation we can figure out how far away the target is. By decreasing the effective range of each node, using TOA techniques we can achieve centimeter-level accuracy in localization. However, this requires dense deployment of sensor nodes or transmitters and it is usually applicable in systems based on acoustic signals [48][27]. RF-based systems, can have bigger coverage area, but provide less accuracy in the range from one to tens of meters [49][30][50].

2.4.2.3 Angle of Arrival(AOA)

Localization can be based on angular estimates as well. Angle of arrival (AOA) is a method which allows a receiver to determine the direction of a transmitter [43][51]. Today, phased array radars [52] and smart antennas [53] can be counted as two popular applications in many places including the military. Using AOA in indoor localization in WSNs is not as popular as the distance based measurement systems. This is because measuring angles is much harder and more expensive and decreasing the size of sensor nodes is impossible if we want to develop a localization system based on AOA [54]. Some factors that effect the accuracy of the AOA system are: directivity of signals in both transmitter and receiver, multi-path reflection, background noise and etc.

2.4.2.4 Comparison between Range-based Localization

Table 2.1 illustrates the advantages and disadvantages of mentioned range-based localization methods. According to this table, we can observe that TOF method has the greatest accuracy. However, RSS-based localization has the advantage of low cost and simplicity. Our analysis conclude, that range-based methods can provide us with an accurate localization system. However, it would be expensive due to hard costs such as additional hardware cost or soft costs such as time and number of repetitions needed for reliability.

2.4.3 Range-free techniques

Although RSS-based methods in the range-based category are cheap in comparison with other methods, they still need hardware and software resources that makes it costly. Examples of smart ideas that have been applied in pursuit of a lower cost system are Centroid [55]and Spotlight[56]. The main idea of range free localization was based on proximity information in respect to unknown objects with known positions [55][57]. But later another idea called "connectivity-based localization" has been investigated by researchers that use local neighborhood sensing to build virtual distances in large indoor areas.

Localization based on proximity is simpler than using traditional ranging methods. If node A senses node B with any kind of technology such as radio or infrared, will report this presence to the base station. Since one of the nodes has known location information (node A for instance), the other one can be considered in the same location with the distance of $\leq R_A$ where R_A is the maximum read range of node A.

Centroid is a practical implementation of the same idea for localization. In this system the target sensor node "j" will receive the information of "k" nodes in its neighborhood . Then the location of the target node can be calculated using equation 2.1 where X and Y are the coordinates of each neighborhood nodes.

Table 2.1: Comparison between Range-based Localization

Method	**Advantages**	**Disadvantages**
RSS-Direct inferring	low-cost sensor nodes, scalable, omni-directional, low computation overhead for ranging	low positioning accuracy, environment sensitive, in-field calibration for accuracy
RSS - Map profiling	low-cost sensor nodes, enhanced accuracy, omni-directional, low computation at nodes	extensive environment profiling and calibration, unscalable, high background computation cost
TOF-Acoustic signal	high accuracy, low timing requirements, low computation and communication overhead	limited effective range, directional, extra sensing hardware, high anchor (landmark) density
TOF-Radio sigmal	better accuracy than RSS direct inferring, large effective range than acoustic systems	ultra-high timing requirements, expensive hardware, heavy computation for signal processing
AOA	additional channel of ranging, orientation information	hardware constraints, computation for effective estimation

$$(\hat{x}_j, \hat{y}_j) = (\sum_{i=1}^{k} X_i/k, \sum_{i=1}^{k} Y_i/k) \tag{2.1}$$

LANDMARC [58] and WCL [59] improved Centroid design by considering weight for the nodes. The idea of giving weight to nodes in localization using proximity is that the anchor which is closer to the target node, should have more weight in location estimation. Both of the mentioned methods use RSS to calculate the weight for each node. Note that in a realistic environment, a larger RSS does not mean that it is closer, except in an anechoic chamber. So mathematical and statistical equations are required at least to decrease the error. For example, LANDMARC uses the following equation to calculate the location of a target node:

$$(x, y) = (\sum_{i=1}^{k} w_i(x_i, y_i)) \tag{2.2}$$

Where

$$w_i = \frac{1/E_i^2}{\sum_{i=1}^{k} 1/E_i^2} \tag{2.3}$$

And

$$E_i = \sqrt{\sum_{i=1}^{n} (\Theta_i - S_i)^2} \tag{2.4}$$

Θ_i is the RSS value in the reference tags and S_i is the RSS value on the reader's side.

Also WCL applies the following equation for location estimation:

$$(\hat{x}_j, \hat{y}_j) = \frac{\sum_{i=1}^{k} w_{ij} \cdot (X_i . Y_i)}{\sum_{i=1}^{k} w_{ij}} \tag{2.5}$$

$$w_{ij} = (P_{ref} \cdot 10^{RSS_{ij}/20})^g \tag{2.6}$$

RSS_{ij} is the RSS value from anchor i at/from node j, P_{ref} is the reference power of radio system and g is a parameter for reducing error and making weak RSS values more effective in the calculation.

Another example in this area is APIT[57]. Figure 2.6 explains the overall design. They segmented the area into a large number of triangular regions with different sets of anchor nodes. The target node receives the messages from those anchors that have common coverage with its location. The overlapping area from all received data can estimate the location of a target node. As you can see in the picture the gray triangle in the figure is the final estimated location of the unknown node.

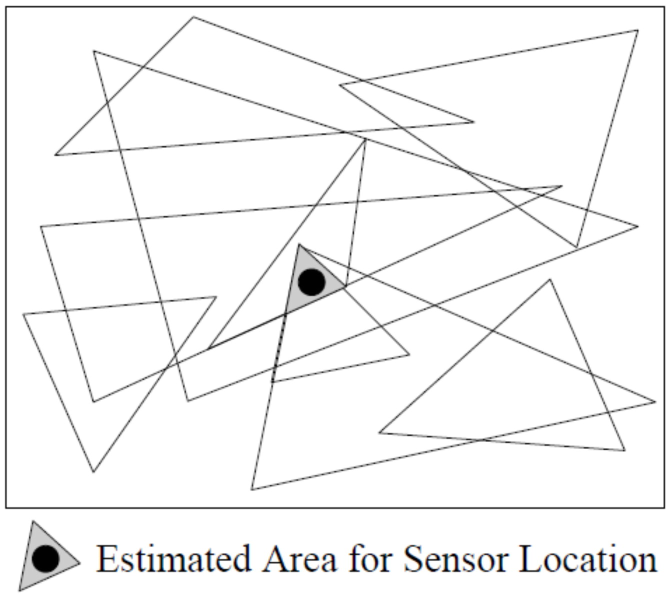


Figure 2.6: APIT: Triangular Coverage Based on Proximity [2]

2.4.4 Indoor Radio-based Real Time Localization Systems

Although outdoor localization techniques have been well studied, and are dominated by GPS technology, IoT and many applications still lack an accurate indoor localization system. Since GPS signals are too weak to be used indoors, indoor positioning (IPS) approaches have to be considered in developing localization.

Mainstream techniques used for indoor positioning are [60]:

- Assisted GPS (A-GPS)
- Inertial navigation
- Infrared positioning
- Radio-based positioning
- Ultrasonic positioning

- Vision-based positioning

Our focus in this thesis is on radio-based positioning. Usually in radio based systems, we have transponder and receiver on each cycle of data transmission. RFID is not an exception and tag and reader are sender and receiver. Localization can be important for reader and/or receiver(tags in our case). For example, it can be important to find the position of RFID tags covered by RFID readers [58][61], or to find the reader's location with the assistance of reference tags.[62][63]

Ranging techniques such as those we described in the previous section, Received Signal Strength (RSS) [64], Time of Arrival (ToA)[65], Time Difference of Arrival (TDoA)[66], Phase Difference of Arrival (PDoA)[67] can report and estimate the distance from the reader.

Bellow are the principle techniques used in Radio-based localization[68]:

Triangulation

This technique is based on the direction of arrival of the tag signal to multiple readers or receivers. It can also be obtained by measuring the radial distance from the readers. Figure 2.7 illustrates the overall idea of triangulation technique. Direction of Arrival (DOA) can be obtained using different methods such as directional antenna[69][70], phased array[71], or smart antennas.

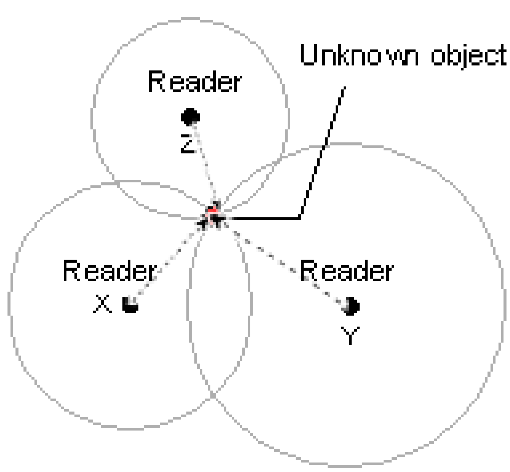


Figure 2.7: Triangulation technique

Radio map

Radio map technique also called "scene analysis", is based on previously measured values in the environment and tries to find the best match with them for localizing unknown location. The values can be signal strength [58] and other parameters, depending the application. Note that accuracy of localization in this method has a direct relation with the number of reference tags. Although there are some techniques to avoid adding more physical reference tags and thus decrease the cost [72], for accurate localization we need more real reference tags.

Trilateration/multilateration

Trilateration determines the location of transponder or receiver using the range information estimated at some reference points. The range can be estimated using any ranging technique mentioned above. Trilateration is easy and useful where a high degree of accuracy is not required [73][74]. RF signals are so vulnerable to be changed in real environments, so measuring based on previous measurements cannot be reliable all the times.

Proximity

Since the range of radio based devices is limited, if the range is not too big, the location of an unknown object can be considered the same as the location of the reader that detected it.[75] In UHF RFID systems, LLRP can report the number of antenna which the tag is read from. So the reference points for detecting the proximity can be just antennas rather than expensive readers.[76]

Radio-based IPS approaches can use Bluetooth, RFID, WiFi and any other wireless technologies. Note that most of them were not specifically designed for localization, so several modifications or add-ons to the system are needed in order to make them capable of localizing.

Wireless Local Area Network (WLAN) devices are one example. But they are expensive and also too large to attach them to small things. Also, Ultra Wide Band (UWB) systems have a potential interference with some radar systems in the environment where they share a wide range of bandwidth.

For indoor localization most current systems provide room-level or sub-room level resolution. Since the coverage area and resolution is limited, the cost issue becomes very important in indoor RTLS. A brief list of up-to-date RTLS products and their major applications is listed in Table 2.2. All of the information in the table is collected from their datasheets or their manufacturer's website. As we can see in the table, most of indoor localization systems in the market are based on active tags. Although active systems offer more accurate and reliable system, but they are expensive and require battery replacement routinely.

Also a short comparison table in academic literature is presented in Table 2.3. Since UHF Passive tags have very weak RSSI and varying considerably depending on the environment, the localization based on signal characteristics from the tag is not going to be precise. So there is not any considerable passive localization system based on the techniques that use signal information.

2.5 Localization based on proximity detection

2.5.1 Overview

Proximity detection technology has been a research topic of great interest for decades, but it has drawn new interest in recent years from research and industry because of its ability to address new needs. One example is turning off the smart phone touchscreen when it is held next to the ear. In proximity detection, the location of items is not of interest. On the other hand, the distance between objects is important. Reporting this information opens up a large number of applications from energy harvesting to automatic control systems and medical care systems.[84]

Proximity detection can have different levels of intelligence depending on the application. Automatic doors were an early form of proximity detection based on IR sensors. Later, automatic toilet flashers and faucet controls became popular. Although these sensors can detect proximity, all of them are big, power hungry, and not intelligent enough for detecting the identification of the object. Traditional proximity detection systems could only identify an object in the vicinity. When RFID showed up, it opened a new window to the application of detecting proximity. Since each tag has a unique ID in RFID, we can determine the identity of two objects and run more intelligent applications: detecting people's interaction [85][86], nurse monitoring in health care [87], tracking people's activity in work area [85] and etc. In this thesis our focus is on proximity detection with identified objects or persons.

There are three general approaches to sensing proximity:

1. Detecting physical contact

Physical contact detection with an object is the most basic kind of proximity sensing. Pressure sensors, touch sensors, and capacitive field detectors are some technologies that have

Table 2.2: Real time Localization Systems on the market

System	Vendor	Technology	Ranging	Accuracy	Applications
AeroScout RTLS	AeroScout	WiFi and Active RFID	TDOA, RSSI	5 meter	Healthcare, Manufacturing, Logistics
ZOMOFI	Albis	Active RFID	Not known	0.5 - 2m	Not known
Axcess RTLS	Axcess	Active RFID	Not known	Not known	Logistics, Security
CenTrak RTLS	CenTrak	Infrared and Active RFID	Not known	Rack-level	Healthcare
Wireless Location	Cisco	WiFi, Active and Passive RFID	Not known	Not known	Asset Management
Ekakau RTLS	Ekakau	WiFi	RSSI	Sub-room	Healthcare, Retail, Logictics, Manufacturing
LOST	Essensium	ZigBee	TOA	Sub-meter	Logistics
Argus	Guard RFID	Active RFID	Not known	3-5 meter	Industrial, Healthcare
SensorSMART	Identec	Active RFID and WSN	Not known	Not known	Marine, Oil, Mining, Defense
BizTalk RFID	Microsoft	UWB and RFID	Not known	Not known	Manufacturing
RTLS ENGINE	Motorola	WiFi, Active and Passive RFID	Not known	Not known	Asset Management
Omnitrol RTLS	Omnitrol	WiFi, UWB, and RFID	Not known	Not known	Manufacturing, Retail, Logistics
PanGo Locator	PanGo/Cisco	WiFi and Active RFID	RSSI	Not known	Asset Management, Healthcare
PervTrack RTLS	PervCom	Active RFID and WSN	Not known	Not known	Manufacturing, Mining Industry
PINC RTLS	PINC	Passive RFID	Not known	+/- 1 spot	Yard Management
Radianse RTLS	Radianse	Active RFID	Not known	Not known	Healthcare
Asset Manager	RF Code	Active RFID	Not known	Sub-room	Asset Management
RFind RTLS	RFind	Active RFID	Not known	Not known	Automotive, Logistics, Manufacturing, Public Transit
SmartChain	Savi	Active RFID	Not known	Not known	Aerospace, Defense, Logistics, Natural Resources
High Definition	Sonitor/IBM	Ultrasound	Not known	Sub-room	Healthcare, Homecare
Plus, PlusON	Time Domain	UWB	Not known	Not known	Retail, Manufacturing, Healthcare, Defense
Ubisense RTLS	Ubisense	UWB	AOA, TDOA	15cm	Manufacturing, Defense, Transpotation
WhereNet	Zebra	WiFi and UWB	TDOA	Not known	Asset Tracking, Supply Chain Management

Table 2.3: Comparison between different localization solutions in academia

System	Technology	Method	Accuracy
whereNet [77]	Active RFID	TDOA	2-3m
LANDMARC [58]	Active RFID	RSSI	1-18m
Multifrequency [78]	passive RFID	phase	80cm-4m
Phase [79]	Passive RFID	phase	1m
Cricket [27]	Ultrasound +RF	TDOA	10cm
WISP [80]	Ulrasound+RFID	ToA	1.5cm
A. Chattopadhyay *at al*[81]	Passive RFID	RSSI	60 cm
R. Miesen *at al*[82]	Passive RFID	phase	N/A
A.P. Sample *at al*[83]	Passive RFID	Optical localization	N/A
Sense-a-Tag (this thesis)	passive RFID	Proximity detection	30cm

been used for sensing physical contact. Contact, a system for intra-body data communication among objects in direct contact with a person's skin is using capacitive field detection technique[88]. The same technique has been used to implement a Touch Mouse in [89].

2. Monitoring wireless cellular access points

Monitoring when a mobile device is in range of one or more access points in a wireless cellular network is another implementation of the proximity location technique and is illustrated by Figure 2.8. Active Badge Location System [90] and the Xerox ParcTAB System [91] are exampels of such a system. Both using diffuse infrared cells in an environment. The Carnegie Mellon Wireless Andrew [92] using a campus-wide 802.11 wireless radio network is another example.

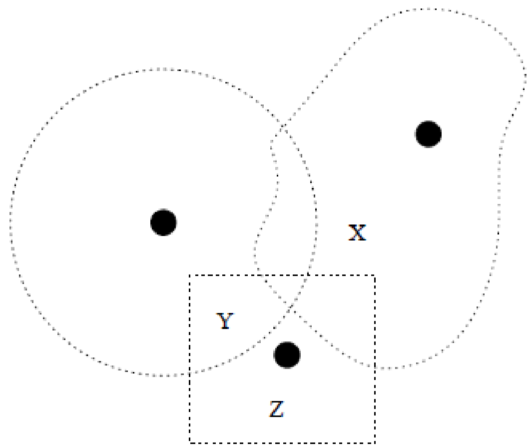


Figure 2.8: Objects 'X', 'Y', and 'Z' are located by monitoring their connectivity to one or more access point in a wireless cellular network. The cell geometry is dependent to the wireless technology technology used in the implementation. For example, X in the picture is a radio cellular network with the shape of the region containing object 'X' while diffuse infrared in a room is constrained by the walls resulting in a square shape which illustrated by the area that contains 'Z'[3].

3. Observing automatic ID systems

In this method if the reader interrogates the tag, or monitors the transaction which has a known location, the location of the mobile object can be inferred. This technique uses automatic identification systems such as credit card point-of-sale terminals, electronic card lock logs, landline telephone records, and identification tags such as electronic highway E-Toll systems[93].

2.5.2 Proximity detection with proximity sensors

Any sensor that can detect the presence of an object without any physical contact, can be called a proximity sensor. Depending on the application, proximity sensors work on different bases. For example, a capacitive photoelectric sensor can be used for plastic targets, for metal objects inductive proximity sensors are more useful. Below are some types of proximity sensors that are already in the market:

- Capacitive
- Passive optical (such as charge-coupled devices)
- Passive thermal infrared
- Photocell (reflective)
- Ultrasonic sensor (sonar which runs in air)
- Inductive
- Laser rangefinder
- Doppler effect (sensor based on effect)
- Eddy-current
- Magnetic, including Magnetic proximity fuse
- Capacitive displacement sensor
- Radar
- Reflection of ionising radiation
- Sonar (typically active or passive)

Generally, we can define two variables for all proximity sensors: proximity range and separation range. Proximity range is the nominal range that a sensor will report the presence of object. Separation range is the nominal distance that a sensor can report the absence of an object which was in vicinity. In some cases these two ranges are almost the same. But it might be different too. Figure 2.9 illustrates a sensor model. R_e is the area that chance of detection decreases with the distance from the reader.

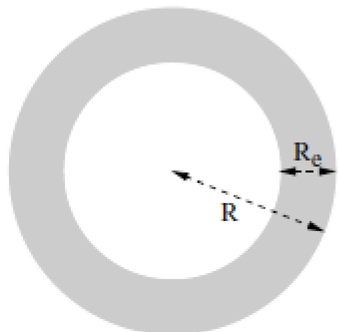
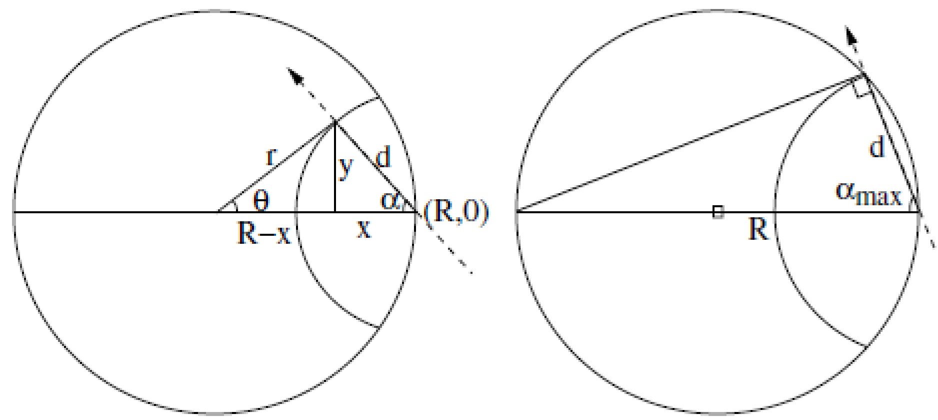


Figure 2.9: Proximity sensor model [4]

As previously stated, proximity sensors do not require any physical contact, so they usually have a high reliability and long life, since mechanical issues such as fraction do not exist. International Electrotechnical Commission (IEC) 60947-5-2 [94] defines the technical details of proximity sensors.

As referenced [4], researchers used binary proximity sensors for tracking the targets. Sensors provide one bit of information regarding a target‘s presence or absence in their vicinity. In this system, a WSN with "n" known-location sensor nodes was considered. Each node is actually one proximity sensor. Nodes records the detection duration and time. A distance-based weighting scheme implemented in the algorithm is used for tracking the object. We borrowed Figure 2.10 to explain the system's functionality better. As you can see in the picture, each node has a circular read range, so the object can enter a sensor sensing range from any point or angle. Each node records the time of presence in the vicinity. The researchers assume that the target is at the boundary of the detecting range at the time of detection. By considering the average speed based on previous detection by other sensors they can estimate the angle of entry by calculating the distance d from the time of detection and separation. Finally, using particle filtering and some probabilistic equations, they try to reduce the error in tracking.



(a) target position after traveling *d* with entrance angle α

(b) maximum entrance angle α_{max} given distance *d*

Figure 2.10: Target tracking model in [4]

Similar work was presented in [95]. The main difference in this work is that it includes the binary information of whether the object is moving toward the sensor or away from it. These researchers also developed a particle filtering style algorithm for tracking the target using proximity sensors. IR sensors in each node report the proximity in WSN. Range of detection is justified by choosing a threshold that satisfies the desired proximity range.

The "Active Badge" [90], is another example of proximity sensors used in indoor localization. This project developed at Olivetti Research Laboratory, used infrared technology to realize indoor localization. However, it did not solved the big problem with indoor proximity sensors- the line-of-sight requirement and the short range of signal transmission.

2.5.3 Proximity detection with active tags

The specification of active tags was discussed in section 3. Since there is an on-board radio and battery in active tags, they have multiple times more read rage than passive tags. Also, the tag can run different algorithms. Because of all of these capabilities, active tags have been considered a good solution for localization and proximity detection.

The "Active badge" system can be named as the first archetypal indoor active localization system[90]. It consists of a cellular proximity system that uses diffuse infrared technology. Figure 2.11 is a sample badge that people should wear and carry to be able to be localized.

The badge emits a globally unique identifier every 10 seconds or on demand. A central server collects this data from fixed infrared sensors around the building, aggregates it, and provides an application programming interface for using the data. The biggest problem with the Active Badges system was its sensitivity to fluorescent lighting or direct sunlight causing problems with infrared connectivity.

Figure 2.11: Olivetti Active Badge (right) and a base station (left) used in the system's infrastructure [3]

LANDMARC system [58] is an indoor localization system based on proximity detection. We described the functionality of this system in section 2.4.3. This system considers active tags as reference points for localization. LANDMARC uses the notion of reference tags (whose locations are known before) and track the tag's nearness to reference tags by the similarity of their signal received at multiple readers in the environment.

EnHANTS project is based on UWB communication and focuses mainly on energy harvesting [96]. Proximity detection can be explored since the communication range between the devices is relatively small. The communication between wireless units is not based on backscattering and therefore it is more power-consuming than passive RFID.

Another popular proximity detection application is for monitoring daily activities of people. The solution in [97] describes miniature HF RFID reader that can be attached to the wrist or as a glove and be used to detect tagged objects that have been touched.

OpenBeacon [86] is the most well-known active tag based system for proximity detection. This project founded in 2006 by the Bitmanufaktur company is an open platform for active

RFID applications.

Researchers at [5] used OpenBeacon active tags to design a person-to-person interaction detector system. They attached an active tag to each participant at a conference. By gathering information about individual's interactions, they were able to identify the patterns of interaction. Some sample models are shown in Figure 2.12. Each tag has a unique ID and identifies one person. In addition, times for each interaction were saved in the host computer. Using the model and stored information, they were able to estimate people's interaction with each other with reasonable accuracy.

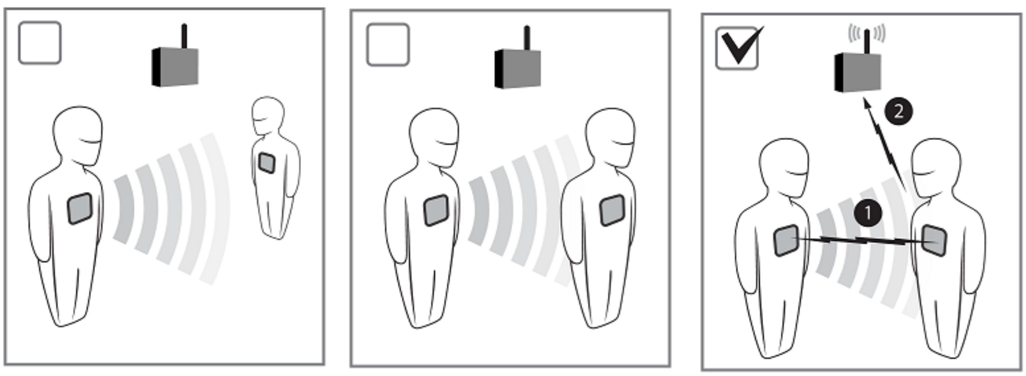


Figure 2.12: Target tracking model in [5]

2.5.4 Localization, proximity detection and tracking with passive RFID

RFID can meet IoT requirements in many ways. Passive UHF RFIDs do not have batteries and therefore the BOM of passive UHF RFID systems is low. The functionality of passive UHF RFID tags has grown a lot. It opens an opportunity to make RFID suitable for a remote two-way communication by modifying RFID readers. In [98] researchers are showing how communication can be done via mobile IPv6 and how passive RFID can be part of that. They modified the RFID readers and low cost tags to be able to communicate two-way end-to-end remotely. Nokia introduced a concept of new radio frequency identification system based on Master-Slave RFID reader architecture. The proposed system will reduce the power consumption and decrease the processing time because of its ability to filter information in the system. They introduced this system suitable for smart homes to do special jobs such as washing, cooking, shopping, etc [99]. The system consists of some master readers, a number of slave readers and some mobile RFID readers which can all communicate with each other and transfer UHF tag information through the internet. They also counted localization and proximity detection as one of the capabilities of the system.

Researchers in university of Washington deployed a big RFID-based network with hundreds of antennas and thousands of tags in [100]. They presented the challenges with RFID networks including: object's material, orientation of antennas, how the tag is mounted to the object, input data error, unpredictable input streams and privacy challenges. They used proximity detection to monitor people interaction in their network. Their system is based on detecting a tag in the coverage area of special antennas. Then based on received EPCs from tags, they process all the information and estimate the possible location and track people in the indoor area.

There are some other solutions for passive systems. But they are integrated with another technology like camera or ultrasound [83][80] or are not accurate enough [79]. Another problem with current passive localization systems is their need of using multiple reader and antennas which increase the cost of the system. For example in [81] neural networks have been used to train the system based on previously collected RSSI values. Even though the area of operation is small (2mx3m), the localization error is about 60 cm on average. In our method, the average error is less than 30 cm depending on the number of deployed landmark tags.

In [101][102], an RFID-enabled IoT solution was presented. It is based on UHF RFID readers placed in a building and passive UHF RFID tags attached to people and objects of interest. The system was extended with a number of software applications that allowed searching for things, integration with social applications, tracking personal trends and so on.

The work presented in [103] describes tags that are able to power themselves and communicate based on the ambient RF. These tags communicate using backscattering and are able to detect proximity of one another up to 2.5 ft distance outdoors. The solution is not based on UHF RFID and does not support UHF RFID passive tags covered in this paper.

The range estimation performance from the RSS is known not to be reliable especially when the system operates in a complex propagation environment. In addition, as pointed out in [79], the tag backscatter loss varies with the power incident on the tag because input impedance of RFID tag IC is power dependent. RSS is also angle dependent. Therefore, different techniques such as fusing tag detection rate with the RSS values or using neural networks to train the system based on previously collected RSS values [81] are used to improve the localization accuracy of RSSI based systems.

Landmark-based techniques are mainly based on comparing the RSS values of the tags placed at known locations with the RSS of the tag that needs to be located. Due to the problems with RSS mentioned in previous paragraph, calibration of the system based on landmark tags is difficult.

Phase-based techniques can be used to improve the accuracy of RSS based techniques for RFID readers that provide phase information (that are not common yet). The solution in [79] describes an experiment using time difference phase-difference of arrival that shows that it is feasible to detect ingress/egress direction of the tag movement and the point when the tag crosses the center. Single frequency narrow-band holographic method to localize passive UHF RFID tags is presented in [82] where the localization is based on phase values sampled from a synthetic aperture by a RFID reader antenna that is moved along a known trajectory. Simulation results show the error of 50 cm can be achieved. It has been shown that the performance of PDOA and RSS techniques in NLOS environment drops up to three times.

Techniques where passive RFID systems are enhanced with other technologies such as ultrasound or cameras outperform RFID-only techniques regarding localization accuracy. Wireless Identification and Sensing Platform (WISP) tags are extended with LEDs that allows optical locating tagged items with millimeter accuracy [83]. The system consists of a WISP tag with acoustic tone-detector that receives and times ultrasound signals, UHF RFID reader, and an array of ultrasonic beacons.

Sherlock [104] uses both a camera and steerable antenna to localize the items. In the RFID endpoint, an RFID antenna is attached to a stepper motor and rotates and changes the power transmission continuously. It scans and processes the number of reads per each angle and power and finally processes the data using a special algorithm. In their scenario, the most recent time the object was detected, the id(s) of the antenna that detected it will be reported, and the location of the tag will be estimated. In the camera endpoint, Sherlock scans the area. If a new object enters the zone and gets detected by the RFID antenna, the camera will synchronize itself with the corresponding antenna angle that detected the item for the first time. Then that picture is stored in the database. By this way when somebody is searching for an object, it will search in the database and move the camera to the stored position in the database.

There are several solutions that have been introduced to augment existing UHF RFID systems in which proximity detection is larger than 50 cm. They are: the ST-based system [105] presented in this thesis, the Gen2 listener [101] and Augmented RFID receiver (ARR) [106], and the Tag-to-Tag communication system [13]. Table 2.4 compare these solutions for proximity detection and localization with some others that described before. These systems allow for detecting communication of passive RFID tags that can be used for localization, proximity detection, protocol analysis, and data collection. The ARR has lower cost and lower detection range than the SDR. However it is still too expensive for ubiquitous deployments required for IoT applications. The ARR and SDR systems are not mobile and can be used only as landmark tags which is too expensive for localization applications.

UHF RFID systems have some disadvantages. Although IC companies introduced new tags with more capabilities, there are still problems with read range, sensitivity, security, etc [107]. Many expensive readers are needed in some localization or proximity detection methods. Data processing complexity is another issue with UHF RFID systems. Again, because battery-less tags are not able of performing even simple processing, the work load is then very high on the host computer. To overcome these issues, researchers suggest an additional component to a general RFID system. In the next chapter, we will name some augmented devices that have been introduced to the RFID system to decrease its limitations.

Table 2.4: Comparison between different technologies in passive RFID localization and proximity detection

System	Technology	Localization Method	Localization Accuracy	Standard RFID components	Main applications
RFID IoT [102]	Passive UHF RFID	Reader range	Reader range	Standard UHF RFID readers and tags	Tracking peopleâĂŹs behaviour
Smart-home RFID [99]	Passive UHF RFID	Reader range	Reader range	Non standard RFID âĂŞ mobile listeners, master and slave readers	Smart homes
WISP with LEDS [83]	Passive UHF RFID, LEDs, camera	optical methods	<1 cm	Modified UHF tag, standard RFID reader, camera	
Sherlock [104]	Passive UHF RFID, camera	cameras	1 m	UHF RFID with steerable antennas and with cameras	Finding objects in the environment
Hand-on RFID [97]	Passive HF RFID	Proximity	N/A	Standard HF RFID system	Detection of daily activities
ARR [106]	Passive UHF RFID	Proximity	N/A	Standard UHF RFID with ARR	Portal
Gen 2 listener [101]	Passive UHF RFID	Proximity	N/A	Gen2 Listener	Protocol analyzer
Sense-a-Tag [105]	Passive UHF RFID	Proximity	30cm depending of the density of landmark tags	Standard UHF RFID with ST	IoT based on standard UHF RFID: Localization, Proximity detection

Although RFID considered as a best solution for globalizing the indoor localization and IoT, but still there are some problems with it including: security, multiple reading of each tag, unreliability, etc.

Chapter 3

Description of Sense-a-Tag

3.1 Overview

This chapter presents the description of Sense-a-tag (ST) and shows how this new device(hardware) augments regular RFID systems. We describe the capabilities of ST and show how it can help develop the Internet-of-Things. Finally we compare it with similar devices that have been introduced by other researchers.

3.2 ST and similar UHF RFID solutions for proximity detection

The research in [105], [108] and [109] introduced a novel RFID system which contains, in addition to tags and readers, a component called "Sense-a-Tag" (ST). A ST has several distinctive features. It can passively detect and decode backscatter signals from RFID tags in its proximity, perform basic processing and communicate the acquired information to an RFID reader by backscattering, using standard RFID protocols.

STs are deployed throughout the space of interest or placed on objects or people. They may be equipped with sensors whose measurements can be conveyed to an RFID reader by backscattering. A ST can listen to the communication between other tags and readers if it is physically near the tags. If the locations of the STs are known, an RFID system with a network of STs has an exceptional advantage over traditional systems for fine grain localization, real time tracking and monitoring.

There are several solutions that have been introduced to augment the existing RFID systems. They are: the ST-based system presented in this chapter, the Gen2 listener [101], Augmented RFID receiver (ARR) [12], and the Tag-to-Tag communication system [13]. These three systems all allow for detecting communication of passive RFID tags that can be used for localization, proximity detection, protocol analysis, and data collection. Figure 3.1 shows the overall concept of all mentioned systems. The light in this picture can be a good representation of the reader. Without the light, nobody can see each other. But when the reader start to communicate with one of the men in the coverage area, they can also see each other. The girl cannot be seen by none of them until entering to the coverage area of the reader. Bellow, we briefly describe each of solutions. Later, we compare these three systems and the ST based RFID system.

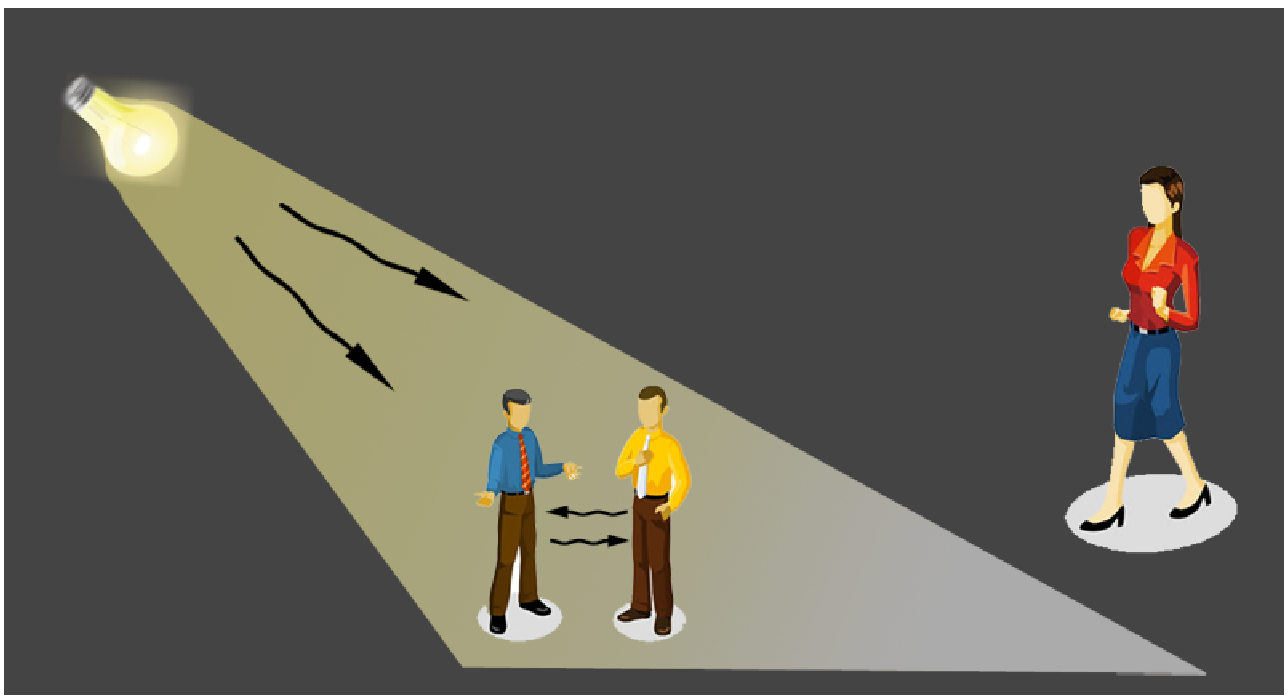


Figure 3.1: Overall concept for RFID augmented devices

Augmented RFID Receiver (ARR)

Augmented RFID Receiver (ARR): A receiver that can sense UHF RFID tags around it is developed in [12]. The ARR uses a method called synchronous detection to overcome the frequency offset challenges associated with intercepting tag signals using a non-envelope detection scheme. This system captures the data by an off-the-shelf UHF

RFID reader IC and then sends and processes the data using an FPGA hardware and a soft-core processor. The ARR has high power consumption and it communicates with the host through Ethernet, and as such it cannot be used for portable applications. The ARR is a high performance high cost component that can provide fast communication to the host and can be used as a landmark tag or a protocol sniffer.

Software Defined Radio (SDR)

Software Defined Radio (SDR): In [101], researchers introduced an RFID device that acts as a UHF reader without downlink (reader-to-tag) transmission. The device is called "Listener" because of its ability to receive and decode the radio signal from both tag and reader. The Listener was implemented fully in C++ and Python and can be run on a Linux PC. The code is based on GNURadio and is released with GPL license. As the ARR, the SDR requires high power consumption and has no mobility. Furthermore, the very high cost of the SDR makes it an unsuitable device for the IoT.

Tag-to-Tag Communication System (T2T CS)

Tag-to-Tag Communication System (T2T CS): Researchers at Intermec Technologies Corporation introduced a passive RFID system called a reader tag, which is based on a low power microcontroller [13]. In this system, the tags establish communication in the presence of an RFID reader. The reader tag communicates with standard UHF passive RFID tags by backscattering the RF wave from the reader. The limitation of this system is that the antenna of the listener and reader tags must be coupled and the maximum read range is only several centimeters.

In the table 3.1 we compare the ST with the three other UHF RFID systems that can detect the proximity of passive tags. The Gen2 Listener offers the best performance in detecting passive tags, but it has the limitation of high cost of the devices. ARR has a lower cost and lower detection range, however it is still too expensive for the ubiquitous deployments required for the IoT applications. ARR and SDR systems are not mobile and can be used only as landmark tags. The T2T CS system has a too low detection range to be of practical use in the proximity detection or localization.

3.3 Functionality of the ST

None of these three similar systems provide cost-effective support for localization of passive tags or a way of detecting proximity of other tags. ST introduces an RFID system that can

Table 3.1: Comparison of UHF RFID solutions for proximity detection

Criteria	**Devices**			
	Sense-a-tag	ARR	SDR	T2T CS
Detection range of passive tags	1 m	3 m	10 m	2.5 cm
Near/far field	Far-field	Far-field	Far-field	Near-field
Cost	25$	115$	750$	15$
Power consumption	Medium	High	High	Low
Applications	IoT Tracking Localization Social-interaction Data collector Proximity-detection	Analyzer Localization Data collector	Analyzer Data collector	Very close proximity detection

perform these tasks and others cost effectively. The ST-based UHF system is composed of standard tags, readers, and the novel ST component. The ST has properties that are useful for the IoT. They are as follows:

- It is able to decode backscattered communication from nearby tags and to communicate with the reader as a regular tag. In other words, the ST is an IoT tag that can hear the communication link between EPC-Global Class 1 Generation 2 [1] UHF RFID readers and tags.

- It is able to store the ID numbers of the detected tags, which can be used to establish association between the STs and the tags. Based on this information, the system is able to infer the locations of the tags or detect the proximities among the tags and the STs.

- It is able to communicate with a reader by backscattered communication. This means that its communication can also be detected by other STs, thereby allowing communication among multiple STs.

- It can be programmed to be situation sensitive and to detect and sense only particular tags. The ST communication is based on RFID interface and does not require any other network infrastructure besides RFID readers. This property, together with its low cost and relatively low power usage, makes the ST a more suitable device for the IoT than solutions based on ARR and SDR.

3.4 System level design

In this section, we provide technical details about the ST. We also describe how the host and the STs work together to detect proximities. The ST is a semipassive EPC Gen 2 compliant device that operates in the range of 902-928 MHz. It uses a battery to power the digital and analog electronics. Specific components used in building the ST include:

- Antenna: LAIRD Tech- Omni directional antenna, 3dBi gain, model CAF95956.

- FPGA: Xilinx Spartan 3AN.

- Battery: Alkaline 9 volts 2100mAh battery.

The detection range of passive tags of the ST is 1-2 m. It has been extensively tested with the IMPINJ Speedway R1000 reader and with different commercial tags using Gen2 chips from Philips, EM microelectronics, Impinj, and Toshiba. A block diagram of the ST hardware is shown in Figure 3.2.

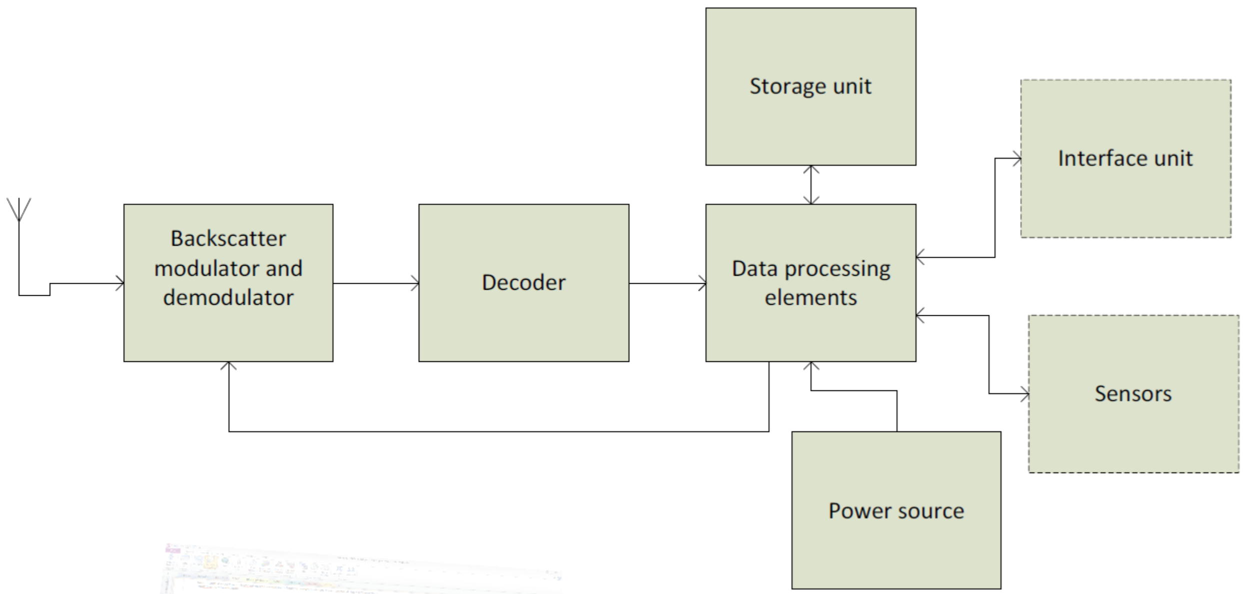


Figure 3.2: Block diagram of the ST

Details of the hardware components of the ST prototype are presented in [105]. The RF front-end of the device is a combination of a passive envelope detector that uses a Schottky diode and corresponding matching circuit. Unlike conventional RFID tags, the STs must be able to sense and decode the backscatter from tags in their vicinity in addition to sensing and decoding reader commands. When a tag in the vicinity of a ST backscatters, the ST receives a superposition of two signals: The weak backscatter from the tag and the much stronger continuous wave from the reader. In terms of the baseband signal, this superposition effectively adds a DC offset to the backscatter signal. The Schottky diode detector detects this signal and feeds it to the analog section for filtering and digitization. The amplitude, frequency and pulse width of the signal from the reader are significantly different than those of the tag backscatter. As a result, the analog section of the ST must have variable filtering and threshold generation circuits in order to reliably digitize the reader signals and the tag backscatter. The output of the decoder is the input to a data processing element which implements the ST protocol. A Xilinx Spartan 3AN FPGA is employed as a processing engine in the digital section of the ST. This platform has been chosen for its rapid prototyping and its ability in parallel processing of the reader and tag signals. The storage unit keeps the IDs of the acquired tags and possibly data from sensors connected to the ST (e.g., temperature or humidity). The blocks that are presented by dotted lines have not been implemented in the current ST version. They include sensors as well as additional interface blocks such as, for example, ZigBee. These blocks would allow the ST to become an interface between the RFID system and standard wireless sensor networks [110].

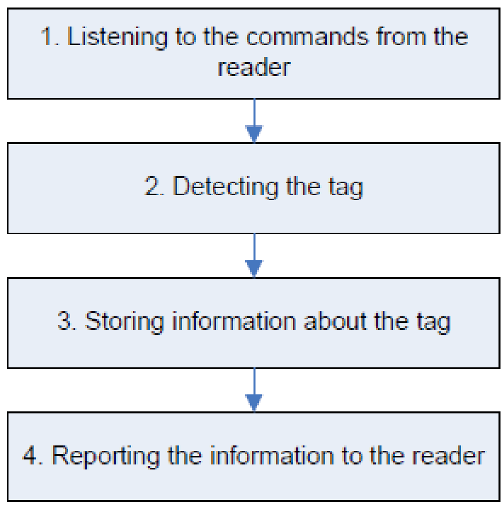


Figure 3.3: The main operational steps of an ST

Next, we describe how the host and the ST work together so that proximity detection can be accomplished. Figure 3.3 shows the main operational steps of the ST. A ST acts as a tag, which means that it can respond to all the commands from a reader in the same way as regular tags. However, it has an important additional functionality: it can listen to the backscattered response from the tags and can discriminate if the reader reads a tag or not. As shown in Figure 3.3, the ST listens to particular commands of the reader for addressing tags (the Select and Query commands as defined in [1]). If the ST detects the command from the reader, the tag's response, and the reader's acknowledgment, then the ST has detected the tag. The information about the detected tag is stored in the ST's storing unit. When the reader singulates the ST, the ST transfers the information about the detected tag(s) to the reader.

Figure 3.4 presents the main operations of the host. In order to incorporate STs into existing RFID systems, the readers have to treat the STs as tags. Since the readers are not aware of the STs and they treat them as ordinary tags, the host has to specify the procedure of reading the tags and the STs. Also, the host understands the ST's operations and it controls the reader using standardized commands. Hence, the host is responsible for intelligent control of the system. The first task of the host is to make sure that the reader first reads tags and then STs. Thus, the reader has to be able to read tags but not STs in the first reading cycle. During this cycle, the STs listen to the tag's responses and store the detected tags' information. In the second round, the reader reads only STs.

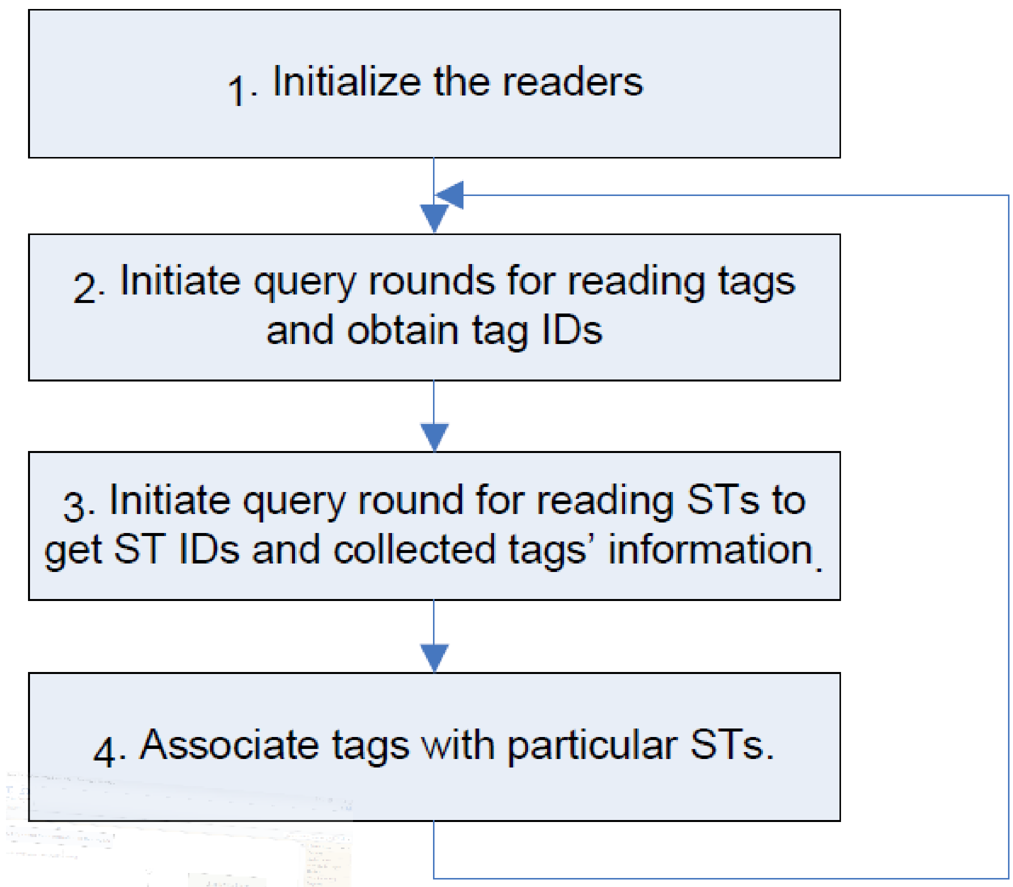


Figure 3.4: Steps implemented by the host for obtaining information from STs through readers

After initialization, the host initiates the query cycle. The tags' ID numbers and STs' information are obtained by the reader and transferred to the host. Next, the host has to analyze the STs' information and relate the tags with the particular STs. The operations of the RFID readers and tags are unchanged. The reader performs reading of the STs and tags based on the command obtained from the host, and it reports to the host all the information that is read.

3.5 Use scenarios

Potential use settings are classified based on the roles of the ST and the tags. We consider two possible placements of both tags and STs: 1) Fixed placement where the tags and/or STs are used as infrastructure components (IC), and they are placed at known locations, and 2) Movable placement attached to objects and/or people (OP).

In Table 3.2 below, we define potential applications of systems with STs based on the placement of tags and STs.

Table 3.2: Potential application of STs based on different placement of tags and STs

ST	**Tag**	**Potential application**
IC	IC	Data filter
IC	OP	-Localization of tags using fixed STs, -Portal application for preventing cross reading of tags, -Data filter
OP	IC	-Localization of STs using fixed tags -Proximity detection among STs
OP	OP	-Proximity detection among STs and tags

Next, we briefly explain how the STs can be used for these applications.

3.5.1 Localization

To support localization, the STs can be used as infrastructure components (landmark tags) placed at known fixed locations. The tags are attached to object or people that need to be located. The location and tracking of the object or people is obtained from the information collected by the STs. Depending on the application, we can exchange the roles of the tags and STs, i.e., use the STs on mobile objects and the tags as landmark tags [105]. The software will decode the information from the STs and determine if the object is in proximity to specific landmark tags. It is clear that increasing the number of landmark tags will result in more accurate localization. When the processing for localization of the collected information from a moving object is carried out sequentially in time, the system can perform tracking and estimate direction of movement of objects or people [109]. At a given time, the location of the desired object or person can be determined. At a subsequent time, a new set of data locates the object or person again, and so on. From the sequence of estimated locations, the system detects if there is movement and determines the direction and speed of movement.

3.5.2 Data filtering

RFID systems produce a large amount of data to be processed. Therefore, this data needs to be filtered. It can be filtered at several levels:

1. Air protocol level, where the reader sends a command (Select command in EPC Gen 2 standard) that causes only tags of interest to respond and send their IDs.

2. Reader level where the reader processes the tags' IDs and removes redundant and static information.

3. Middleware level, removing static information from the list of read tags sent by the reader.

The STs can act as an additional filter. Besides selecting only tags of interest, the system with ST will allow for selecting particular tags at particular places or selecting specific events of interest (interactions, for example). In addition, in current RFID systems, static information means that the tag is being repeatedly read by the same reader antenna. However, the tag can move inside the reading zone of the RFID reader and this move will still be considered static information. With STs, the granularity of tag detection is significantly refined, which improves the process of data filtering.

3.5.3 Unwanted reads

There are two main problems in using RFID for portal applications: (1) the read-accuracy and (2) cross-reading of tags. The read accuracy is the percentage of tags moving through the portal that are correctly read and identified by the portal reader. Cross-reading represents unwanted reads of tags that do not go through the portal. With the RFID passive tag, the read-accuracy depends on the amount of power the reader is able to deliver to passive tags. In order to improve the read accuracy, the power at the output of the reader antenna is increased, which then results in an increased number of cross-readings. So, high read accuracy and zero cross-reads are conflicting requirements.

By using STs, it would be possible to transmit signals from the reader antenna at full power. By properly positioning and shielding the STs, only those tags in the portal areas would be identified. Even if the tags are read by the readers outside of the portal area, they will not be sensed by the STs and therefore will not be registered by the system.

3.5.4 Proximity detection

The main difference between proximity detection and localization is that localization is based on having infrastructure components (either tags or STs) at known locations. For proximity detection, the location of the STs (or tags) is not known in advance and is irrelevant. There are many applications where it is important to detect interactions of objects or to detect proximity between objects without knowing exactly where the objects are.

Table 3.3: Proximity detection applications based on whether the STs and tags are placed on objects or people

ST	**Tag**	**Potential applications**
Object	Object	-Interaction among objects: -IoT applications -Detection if the object is moved from a particular place
Object	People	Interaction between people and objects in situations where the objects are expensive or their number is small so that they are tagged with STs.
People	Object	-Interaction between people and objects: -IoT applications -Tracking daily activity of people. -Tracking interaction with sensitive objects such as blood samples, dangerous chemicals, or explosive devices
People	People	-Interaction among people: -IoT applications -Tracking interactions at social events

Potential applications are presented in Table 3.3. One promising application of advanced

UHF RFID technology augmented by ST, attaches it to a person with cognitive difficulties to track their daily activities in order to keep them safe. In [111], tags are attached to objects of interest and short-range readers are attached to people's hands. This system does not satisfy a basic requirement of the application because it interferes with the person's daily activities. They would have to wear heavy bulky readers on both of their hands. Our new ST-based solution would only require wearing one small ST wristband. The long range RFID reader could be fixed and placed to cover the area of interest without interfering with the individuals activities.

Chapter 4

ST-Based RFID system

4.1 Overview

This chapter proposes a solution to the existing problems that described in previous chapters in the form of ST-based RFID system. In this system, the regular RFID system doesn't need to be changed or modified in both hardware and software point of view. The only change is that a new device called the ST is adding to this system and complements the regular reader-tag RFID system. The ST receives both reader's and tag's signal and report the existence of tags in the vicinity to the reader using RFID interface, Figure 4.1. First, we start with how this system can mitigate the problems. Next, we introduce some applications that ST can be a solution for that in real world and its limitation.

4.2 Mitigating RFID problems

4.2.1 Inexpensive tags, costly readers

RFID tags are very cheap, but are not capable of doing heavy processing. In reverse, readers can run heavy processing algorithms, but are very expensive in cost. So it is challenging how we can implement an RFID system with the best trade-off between cost and capability. By adding ST to the regular RFID system, the performance of the system will be improved. However, the cost of the system will not increase so much. STs can perform some of reader's tasks. In fact, instead of adding one reader, depending on the application, we can add 20 STs to the system.

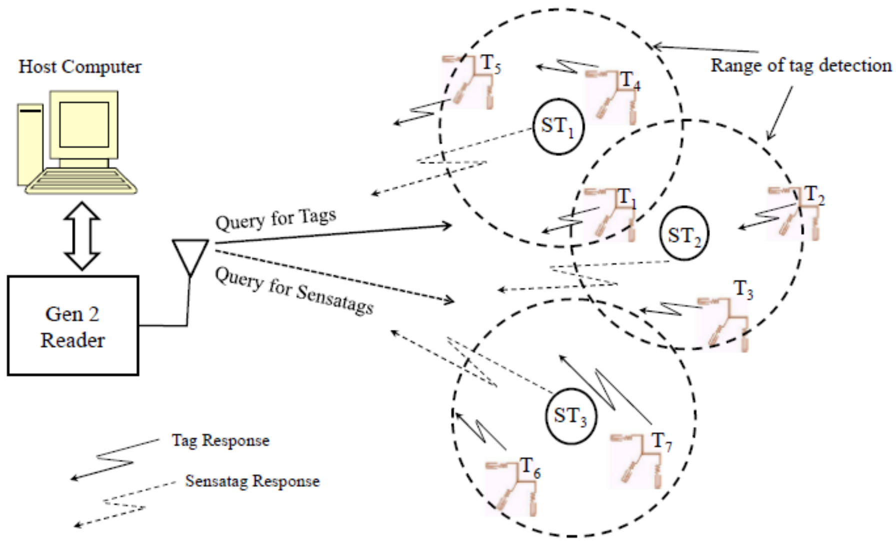


Figure 4.1: ST-based RFID system

4.2.2 Fading, multipath and blind spots

In all RF telecommunication systems there are blind spots in the coverage area. Objects in the coverage area are affected by fading and multipath, so the number of blind spots (the locations that the reader cannot detect the tag inside the coverage area are called "blind spots") can be increased or their place may be changed. Note that blind spots would have to occur for both reader and tag. When the blind spot is caused by the reader, introducing a new receiver that can act as a reader, can decrease the number of blind spots. When the tag receives the power from the reader and backscatters the signal, ST can receive it also and report it to the reader in next query round. ST acts as a reader in first round, listens to the tags in the vicinity and transmits the stored data in next round as a transponder.

4.2.3 Interference

Reader to reader interference is one of the most common issues in RFID networks. ST does not transmit any signal while it listen to the tags and is just a receiver. Using multiple receivers rather than multiple transmitters can solve interference issue, especially in the ISM band where many other devices are working in the same frequency range.

4.2.4 Data processing

As mentioned in the last chapter, RFID tags respond to the reader anytime that reader interrogates the zone. Using LLRP, it is possible to put a mask when it is going to send the query. But it is not applicable solution all the time. For example, if we want to use RFID as a system for localization, we need to interrogate the whole zone and read all the tags. Lets estimate that each tag will be read 15 times/second on average and thousands of tags are in the area. Huge CPU and memory resources are required to process this much data and run the algorithms. ST as an interface between the tag and reader, can just report the valuable information that we need. In this case, the host computer does not need to do the filtering. Just processing the ST's EPC will be enough to localize the item.

4.3 Proximity detection, localization and IoT applications with ST

4.3.1 Overview

In this section we show how ST can help RFID applications with emphasis in proximity detection and localization. Based on different scenarios, we demonstrate the ST‘s role in its corresponding application. Roles of the ST and passive tags can be different for different applications. The tags (or STs) can be used as infrastructure components (landmark tags) placed at known locations and for detecting mobile STs (or tags). In another scenario, both tags and STs can be mobile and the STs can be used to detect proximity among themselves to the other tags. Next, we briefly explain how the STs can be used for proximity detection and reducing cross-reading. Localization is completely based on detecting proximity between the ST and the stationary landmark tags as described in [105].

Potential use settings of ST tags are classified based on the roles of the ST tags and the tags. We consider two possible placements of both tags and ST tags:

1. Fixed placement where the tags and/or ST tags are used as beacon tags (BT), and they are placed at known locations, and

2. Attached to objects and/or people (OP).

Table 3.2 provides potential applications. In this section we focus on how the STs can be used for proximity and localization.

4.3.2 ST as landmark tag

In support to localization, the ST tags can be used as beacon or landmark tags placed at known fixed locations. The tags are attached to objects or people that need to be located. The location and tracking of the object or people is obtained from the information collected by the ST tags. This organization is shown in Figure 4.2. ST-Es in the picture are STs that have been considered as landmarks and ST-R is a representation of a mobile object attached with ST. All the ST-E tags will send the gathered information through RFID interface. The ST-E tags can detect tags and other ST tags in their proximity and report detected result to the host. This use scenario is suitable for the applications where the number of objects to be tracked is large and therefore it is feasible to tag them using passive tags. Finding lost items and searching for objects are two potential IoT applications in this scenario.

4.3.3 ST as mobile tag

Depending on the application, we can exchange the roles of the tags and ST tags, i.e., we can use the ST tags on mobile objects and the tags as beacon tags. The software will decode the information from the ST tags and determine if the object is in proximity of specific landmark tags. This is presented in Figure 4.3. It is clear that increasing the number of beacon tags results in more accurate localization.

The ST tags can be, for example, attached to the wrists of workers. The ST tag is mobile and communicates with the reader using backscattered communication and therefore the ST tags are of ST-R type in this configuration. The beacon tags are labeled as BT and they are placed at fixed locations in each aisle. In practice, more beacon tags are needed for reliable localization than ST-E tags in Figure 4.2. Passive tags (T) can be used for example to label boxes that are on the shelves. In Figure 4.3, the ST-R tag on the left side can sense one tag and one BT. Based on the position of the BT and the response received from the ST-R tag, it is possible to determine the position of the ST-R tag. When the position of the ST-R tag is known and the ST-R tag detected a tag nearby, it is possible to estimate the position of that tag as well. We call this *indirect* localization. Besides localizing nearby tags, it is also possible to infer which objects are nearby. This use scenario is suitable for the following IoT applications:

- Localizing people and/or objects that carry ST tags.
- Detecting proximity between detected objects and possibly inferring their interactions or relationships.

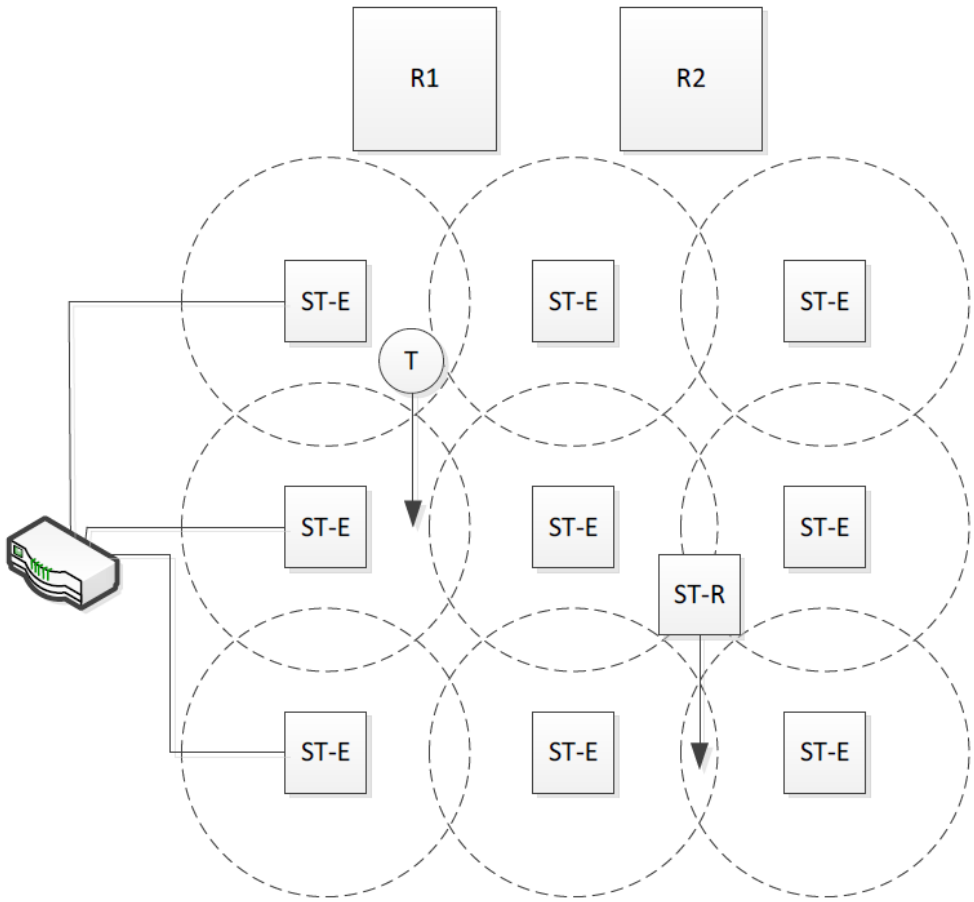


Figure 4.2: Localization of the tags T and ST-R with ST-E tags placed at known fixed locations. There are two readers, labeled R1 and R2. The dotted circles around each ST-E tag represent their detection range.

The advantages of the use scenario presented in Figure 4.3 in comparison with the scenario presented in Figure 4.2 are:

- The infrastructure hardware is much less expensive because beacon tags are inexpensive passive tags.
- The maintenance required would be much less because of the smaller number of ST tags than that in the fixed infrastructure scenario of Figure 4.2.

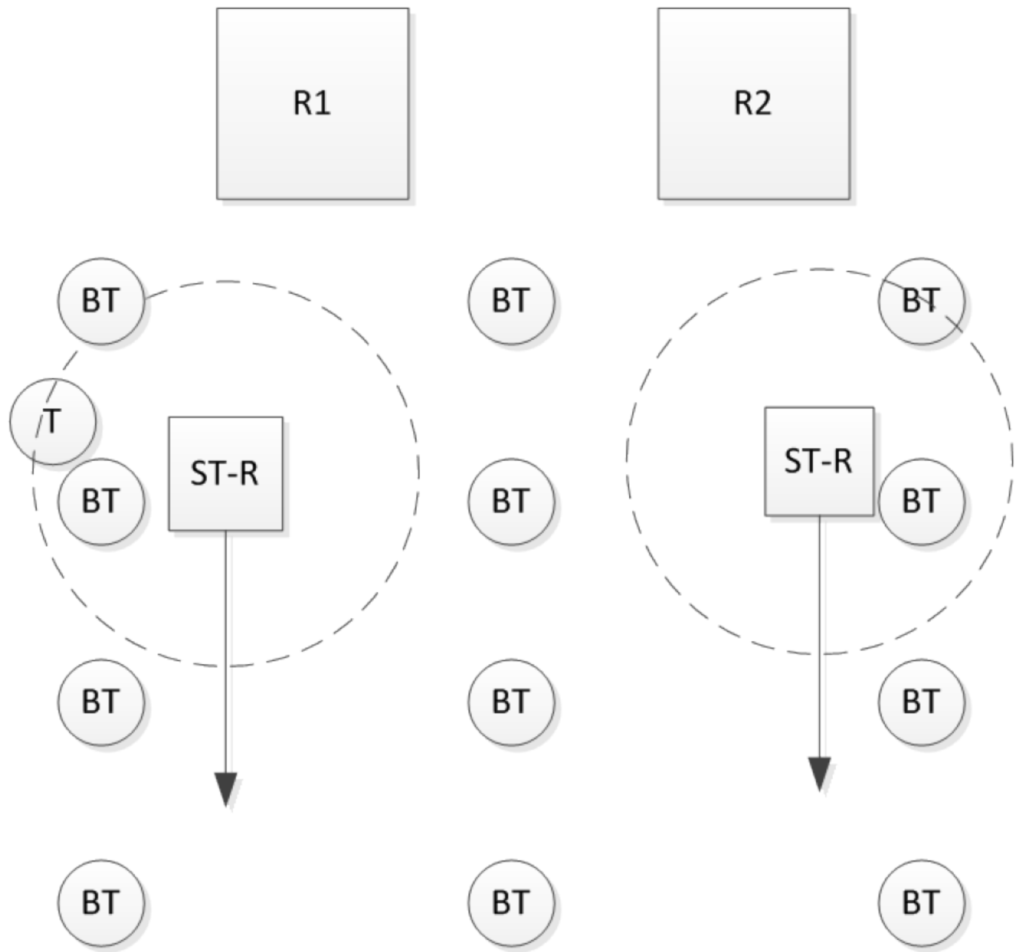


Figure 4.3: Localization of the tags T and ST with passive/semi-passive beacon tags (BTs) placed at known fixed locations.

4.3.4 Unwanted reads

Reliable localization and detection of entrance and exit events are important for IoT applications based on RFID. There are two main problems in using RFID for these applications: (1) read-accuracy and (2) cross-reading of tags. The read accuracy is the percentage of tags moving through the portal that are correctly read and identified by the portal reader. Cross-reading represents unwanted reads of tags that do not go through the portal. With the RFID passive tag, the read-accuracy depends on the amount of power the reader is delivers to passive tags. For improvement of read accuracy, the power at the output of the reader antenna is increased, but then the number of cross-readings is increased. Clearly, high read accuracy and zero cross-reads are two conflicting requirements. By using STs, it is possible to transmit signals from the reader antenna at full power. The STs are deployed to sense tags only in the portal area by properly positioning and shielding the STs. When tags outside the portal area are read by the readers, they will not be sensed by the STs and therefore will not be registered by the system.

4.4 ST-based system vs other solutions

There are different solutions that can localize passive UHF RFID tags. Some of them use only the reader antenna and some use additional technology like infrared for more accurate localization. In this section we discuss about how ST-based system can improve localization accuracy, resolution, speed, cost and etc.

Our experience with RSSI based techniques for localization is that it is very unreliable when the RFID system operates in a complex propagation environment [112]. Shadowing, reflection and scattering are problems not only for signal strength-based techniques but also for phase and time of arrivals based techniques. We will present the Cramer-Rao lower bound [113] for the range estimate using RSS based technique that provides minimum achievable mean square error of a set of parameters. For the range estimation d_{est}, the CRLB due to shadowing effect is presented in equation 4.1 [112]:

$$RMSE(d_{est}) \geq \frac{Const * \sigma * d}{n} \tag{4.1}$$

We see that the error increases with the distance d and with the standard deviation of shadowing σ and decreases with the path loss exponent n. In our application, the threshold for detection of the ST is fixed and based on the received signal strength from the reader. However, the error is small because in most cases the ST and the tag are very close to one another and there is no shadowing. Non-line-of-sight which is a problem for all other methods is not a problem as long as the ST receives the signal from the tag that is above the fixed threshold. So, non-line-of-sight will reduce the read range and detection range of the ST but it will not affect the accuracy of the method if the ST detects the tag. The major difference between the other methods and our method is that the other methods need to estimate the phase or the signal strength based on different mathematical models while our method relies on simple associations when the ST detects a tag in its proximity.

In this thesis we only consider IoT based on off-the-shelf passive UHF RFID systems.

Systems that use other technologies besides RFID are attractive but cannot be used in localization of regular passive tags or detection of their proximity. There are different systems that use different methods such as phased based techniques presented by Intermec [79] or previously patented by Symbol Technologies [114]. But still there is some issues such as phase-based methods are sensitive to phase distortion caused by multipath propagation.

There is two important points that should be considered in comparison for accuracy. First, we need to take into account if the object is stationary or mobile. Second, the accurate methods rely on the accuracy of another technology that has been used such as camera or ultrasound.

The goal of this thesis was to use the existing passive UHF RFID components such as off-the-shelf readers and tags and then to enhance the existing passive UHF systems by adding the new component: the ST. Addition of another technology such as ultrasound requires modifications of commoditized components such as tags and therefore will have difficulties being adopted by the industry. Current UHF RFID systems with stationary readers cannot be used for proximity detection between tagged devices. These tags communicate only with the readers and as such the system would need to rely on determining location of the tags by the reader and therefore determining proximity. As pointed out, traditional RTLS techniques are inaccurate and this scenario would fail. Another approach could rely on having mobile readers that are carried by the users in a similar way as it is done in HF systems. These mobile readers could then detect proximity of other tags. Inexpensive mobile readers that allow for reading up to 1m are bulky, power consuming and still very expensive ($500 minimum). Therefore, the solution that relies on the STs is simpler, more flexible and more reliable.

We will summarize the advantages in comparison with the other systems:

- **UHF RFID systems:** allow for proximity detection, allow for more precise localization that depends less on fading conditions in the indoor environment.

- **HF solutions:** ST-based RFID system is a flexible and scalable solution that can be used not only for tracking interaction between people and objects, but also between people and to localize people and objects.

- **Active RFID solutions:** Even though our ST is still expensive and power consuming, it will be implemented in next iteration to be less power consuming and expensive than regular active tags used for RTLS. The only active solution that we are aware of that supports proximity detection among tags is openbeacon. We are currently experimenting with the openbeacon system and we are getting good results in detecting proximity of people (this is what it has been intended for) but not in detecting objects or localizing people and objects. However, after some modifications, this could also be done.

- **RFID systems enhanced with other technologies:** These systems are not the mainstream and require modifications of off-the-shelf components. However, when line-of-sight is available it is known that ultrasound techniques for RTLS are very accurate.

A comparison table with 14 references used in the paper is presented in Table 4.1. It is important to note that ST-based RFID system does not only improve localization performance of RFID systems but also enables other applications such as proximity detection and portal application. N/A means that the systems are not used for localization. Indirect localization means that the knowledge of the location of one object can help locating other objects. ST advantages are listed in the last column. Advantages and limitations of ST have been described before.

Table 4.1: Comparison table between the different solutions for proximity detection and localization with ST.

System	Technology	Localization Method	Accuracy	Std RFID components	Indirect localization	Proximity detection	Applications	ST advantages
RFID IoT	Passive UHF RFID	Reader range	Reader range	Standard UHF RFID readers and tags	No	No	Tracking people's behaviour	Allowing for proximity detection. Fine grained localization.
RSSI RFID	Passive UHF RFID	RSSI	~ 1 m	Standard UHF RFID readers and tags	No	No	Localization	Allowing for proximity detection. Fine grained localization.
Smart-home RFID	Passive UHF RFID	Reader range	Reader range	Non standard RFID — mobile listeners, master and slave readers	No	No among tags, slave and mobile readers have low range and can be used for proximity detection	Smart homes	[6] is just a conceptual solution that is more complex than ST-based RFID system
Ambient backscatter	Passive technology	Ambient power harvesting and backscattering	N/A — however it is possible to implement localization based on proximity	Non standard	N/A	2.5 ft proximity communication	Power harvesting IoT	Relying on standard RFID components
Enhants]	UWB	Non-RFID — power harvesting	N/A	Non standard	N/A	Yes — in the range of 1m to 10 m	Power harvesting IoT — the goal is to continuously locate and detect proximity	Relying on standard RFID components, Localization
Holographic	Passive UHF RFID	phase	< 50 cm	Standard UHFreader and tags — reader antenna moves at known trajectory	No	No	Localization	Allowing for proximity detection.

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Table 4.1 – continued from previous page

System	Technology	Localization Method	Accuracy	Std RFID components	Indirect localization	Proximity detection	Applications	ST advantages
								No need to move readers.
PDOA	Passive UHF RFID	phase	< 1m	Reader that provides phase	No	No	Localization	Allowing for proximity detection and limiting the range.
WISP with LEDS	Passive UHF RFID, LEDs, camera	optical methods	<1 cm	Modified UHF tag, standard RFID reader, camera	No	No between the tags. It can detect that two tags are located next to one another by the camera.		Much simpler system based on standard RFID tags.
Sherlock	Passive UHF RFID, camera	cameras	∼1 m	UHF RFID with steerable antennas and with cameras	No	No	Finding objects in the environment	Much simpler system based on only on RFID components, proximity detection
Hand-on RFID	Passive HF RFID	Proximity	N/A	Standard HF RFID system	N/A	Detecting touching of objects	Detection of daily activities	ST can be used for much more applications: localization, social interactions
Openbeacon	Active RFID	Proximity and localization based on landmark	∼2m is reported. It can be much less if denser landmark tags are used	Non-standardized active RFID	Yes	Yes < 1 m detection range	Social interaction, Location of people	Active tags are more expensive. For localiz., openbeacon tags need to replace batteries if used as landmark.

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Table 4.1 – continued from previous page

System	Technology	Localization Method	Accuracy	Std RFID components	Indirect localization	Proximity detection	Applications	ST advantages
ARR	Passive UHF RFID	Proximity	N/A	Standard UHF RFID with ARR	N/A	Yes $\sim$ 3 m detection range	Portal	ST can be used as both stationary and mobile tag while ARR is only stationary and it is more complex.
Gen 2 listener	Passive UHF RFID	Proximity	N/A	Standard UHF RFID with Gen2 Listener	N/A	Yes $\sim$ 12 m detection range	Protocol analyzer	Expensive hardware with GNU radio. Stationary compoe-nent.
Sense-a-Tag	Passive UHF RFID	Proximity	30cm — depending of the density of landmark tags	Standard UHF RFID with ST	Yes	Yes $<$ 0.6 m detection range dependant of the distance from the reader	IoT based on standard UHF RFID: Localization, Proximity detection	

The requirements for the IoT are mentioned before in Chapter 2. Bellow we review some of the critical points in IoT applications, specially in tracking humans, identifying tagged object carried by a humans and having tags passing through a portal. Then we explain how ST can provide a better solution in comparison to its competitors.

- **1) Cost:** Most of the localization systems are using multiple antennas and multiple readers to localize the items. In UHF systems, the main cost of the system is on the reader side. Current ST costs about $80 in non-industrial production. However, it will be much less than that in mass production. Besides, lots of optimization need to be done on the hardware part which can decrease the cost to 1/3 of current price such as replacing the FPGA with a low power MCU. In large environments that adding readers is required, ST based systems can decrease the cost effectively.

- **2) Speed:** The speed is currently not high and depends on the implementation of RFID system. In the current implementation, the ST listens and records selected tags in 5 consecutive EPC Gen 2 query rounds. In the sixth round, only STs are selected by the RFID reader and they report their results. The number of query rounds that can be generated in a second is limited with our current reader that we use and theoretically can be much better. Therefore the experiments that were performed in Section D are done with the robot that is moving slowly. Again, this is the limitation of the current implementation and the current technology that we use and will be improved in future.

- **3) Read range** of ST is more than 5 meters by itself. The read range is small for the semipassive tag and it will be significantly improved in our next design. Detection range (resolution) of the ST is in the range of 1-2m. This limited range allows the system to decrease the error in localization and proximity detection applications.

- **4) Read rate** is distance dependent. In that experiment it is clear that the ST is able to detect the tag large number of times when the distance between the tag and the ST is 5 m only when the distance between the tag and the ST is about 0.5 m. However, it is still able to detect the tag less times at larger distances and in many applications this should provide satisfactory results. At this moment the threshold for detection of tags by ST is fixed to a particular power level detected by the tag. One of the future research directions can be to make the threshold adaptive.

- **5) Localization performance:** The performance will depend on the number of deployed landmark tags. The limited range of the ST allows the system to decrease the error in localization and proximity detection applications. Clearly, since RSS of passive tags are not reliable, we tried to use sensing the proximity of tags for localization purposes. Some realistic experiments for localization and tracking will be discussed in Chapter 6. Based on our experiments, the precision of localizing the moving object was very high $<$40cm. In addition, the ST also detects and therefore localizes nearby stationary tags.

- **6) Proximity detection:** UHF RFID systems do not support proximity detection. The works presented in the thesis that we call UHF RFID solutions for proximity detection all require a new component that can detect the proximity. Other RFID systems could be used such as HF or some active RFID systems (openbeacon). As pointed out before, RTLS systems make large localization errors and as such are not suitable for detecting proximity.

4.4.1 Limitations and disadvantages of the STs

The main disadvantage in comparison with some solutions in Table 4.1 is a need for landmark tags for localization applications and the need to change batteries on mobile STs. However, these landmark tags are passive UHF RFID tags which are inexpensive and maintenance-free. Features that need to be improved in the current version of the ST are presented next. The detection range between the ST and the tags depends on the orientation between the ST and the tags. We can improve the detection range if we use dual-dipole passive tags, two tags per object or a semipassive tag.

In order to preserve the same number of detections of the nearby tag by the ST, the detection range of the ST decreases with the distance between the tag and the reader. In case of localization with fixed reader antennas and fixed passive landmark tags this feature can be corrected in software.

In addition, the ST listens to five readers query rounds and reports in sixth. Therefore, the reporting speed of the ST is limited with the current implementation and the protocol used. Since this was the first prototype of the ST its reading range (up to 5 m) and sensitivity are quite low for the semipassive tag. These features can be improved in the next implementation of the ST.

Chapter 5

System and Experimental Designs

5.1 Overview

This chapter explains the design details of the localization system and experimental area including the reader, tag and ST characteristics. The goal of these experiment is to evaluate accuracy of the ST in realistic conditions. We will show how different factors in the environment can affect the accuracy of the results on the system based on ST.

The system was setup in Lab 5130 of the SITE building, located at the University of Ottawa. This laboratory is approximately 10m*6m*3.55m meters.

A software developed in C# has been prepared to simulate and process the information received from the reader.

The reader that is used for this experiments is Impinj R1000 reader [115] from Impinj company. The power output has been set at maximum power, which is 32dBm. The antenna cable has 2dBm loss, according to its datasheet. Thus, the output power at the antenna is 30dBm.

The UHF passive tags for the experiments have been chosen randomly between 200 similar commercial tags from GAORFID. The passive UHF tags have the Philips "MF1S70" chip and a simple dipole antenna.

5.2 Basic Tests

5.2.1 Reader and tag test

The purpose of the reader test is to evaluate the effects of reader position and antenna orientation. A lot of factors may affect the RSSI reading of a RFID system. Detailed analysis of the factors that might affect the read range and RSSI value in RFID systems have been studied in research papers [116][117]. However, to be able to peruse the ST performance and compare it with traditional passive RFID system, we investigate three different factors that have significant effect on the RSSI value. Note that, only reader and tag related variables were considered.

- the distance from the reader antenna to the ground
- the distance from the reader antenna to the tag
- and the reader antenna orientation

These three factors were chosen to be evaluated in this experiment.

The distance from reader to ground

Based on our experiment, the distance from the reader antenna to the ground might effect the RSSI value backscattered from the tag. To test this, we used 3 different antennas with different distances from the ground. Then we measured the RSSI value of backscattered signals from the tag. The experimental set is shown in Figure 5.1. To keep the angle between the tag and the antenna constant, for each antenna we consider only the tags at the same height as the reader antenna.

Figure 5.2 shows the variation in RSSI value backscattered from the tags. Considering only a small number of reads will increase the error of this experiment, because RSSI value of passive tags can be different from one read to another one. To mitigate this error in the experiment, each of the numbers in Figure 5.2 is the average of 500 reads of that tag by its corresponding antenna. As you see in the figure, the signal strength backscattered from the tags that are close to ground, show a significant difference from the other two antennas. At a 3.5m distance from antenna #3 we do not have any reads, while antenna #1 and #2 detect the tags up to 4.5m away. This caused by the change in radiation pattern of the reader antenna caused by the ground and decreasing the read range accordingly.

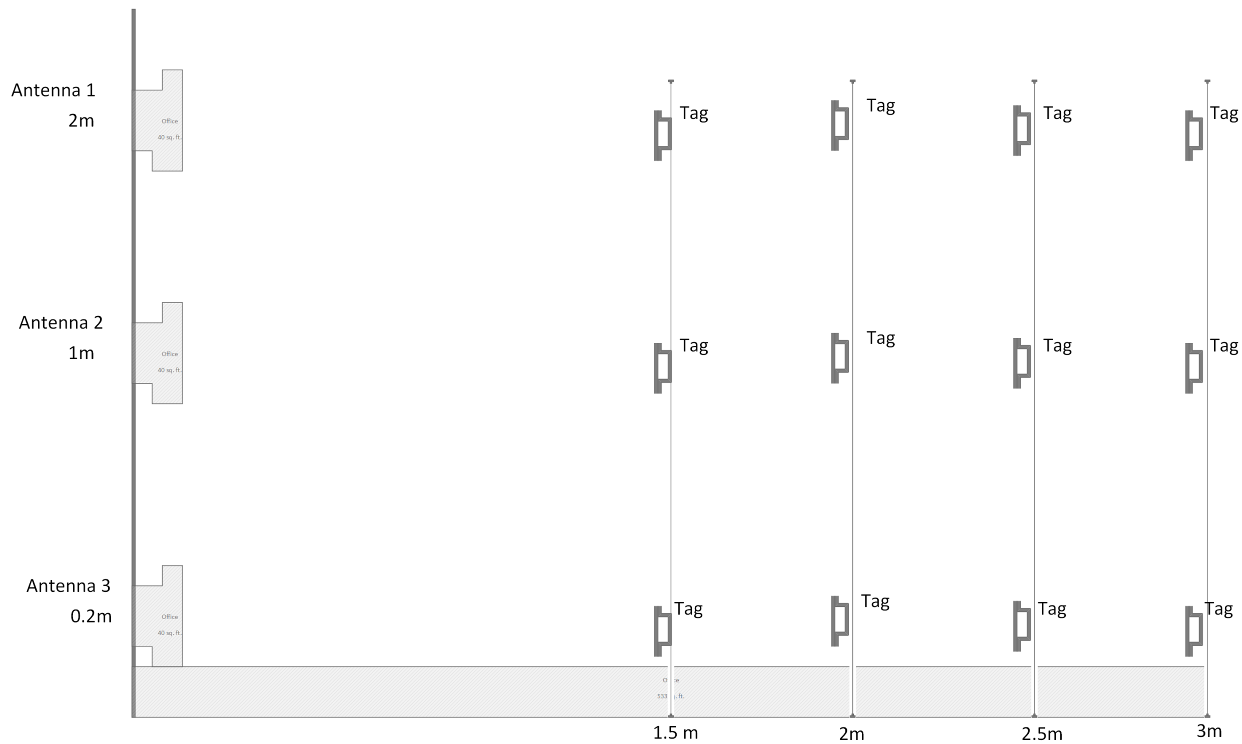


Figure 5.1: Experimental set for evaluating the distance from reader to ground effect on RSSI value

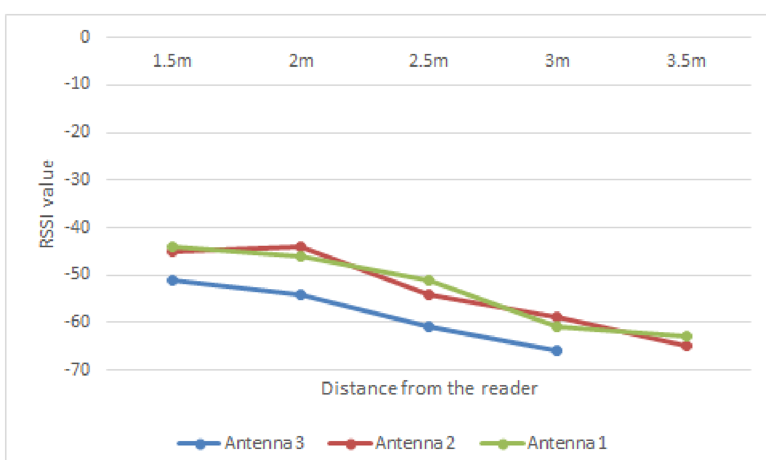


Figure 5.2: RSSI values for different positions of reader antenna and tags

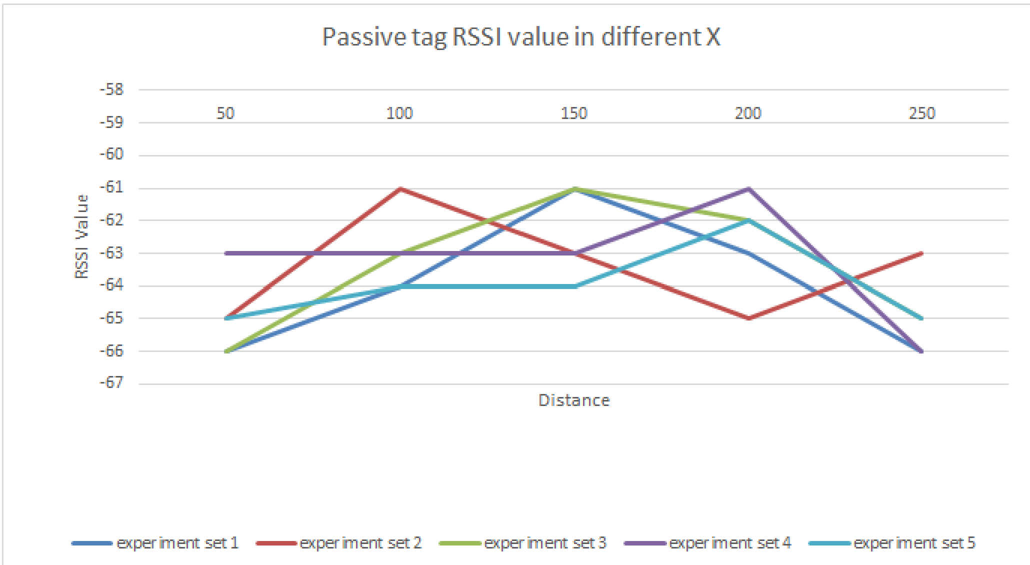


Figure 5.3: RSSI values for different positions of reader antenna and tags when the angle between the tag and reader antnna is 45 degree

The distance from reader to tag

The same experimental set shown in Figure 5.1 has been used for this experiment. In Figure 5.2 we can easily observe variation of RSSI value as the distance from the reader increases. In some cases our RSSI value increases with distance from the antenna. A sample of this situation can be seen at the distance of 2m from antenna #2. The reason for this is that at the previous point (1.5m), we have a fading effect. In the worst case, although we are in the read range of the reader, we do not have any reads. We call this points "blind spots".

Note that the RSSI values in the Figure 5.2 average 500 reads. The angle between the reader's and tag's antenna is in the best orientation in this experiment. Figure 5.3 shows the RSSI value of 5 sets of experiments without averaging. The tag used in this set of experiment (UHF chip from EM Semiconductor) is different from the tag used when the reads were averaged. In this experiment, the angle between the reader antenna and the tag is 45 degrees. The 5 experiment sets were chosen randomly from 500 repetitions. As we can see in the Figure 5.3, the values for each set of experiment are extremely variable due to environmental effects.

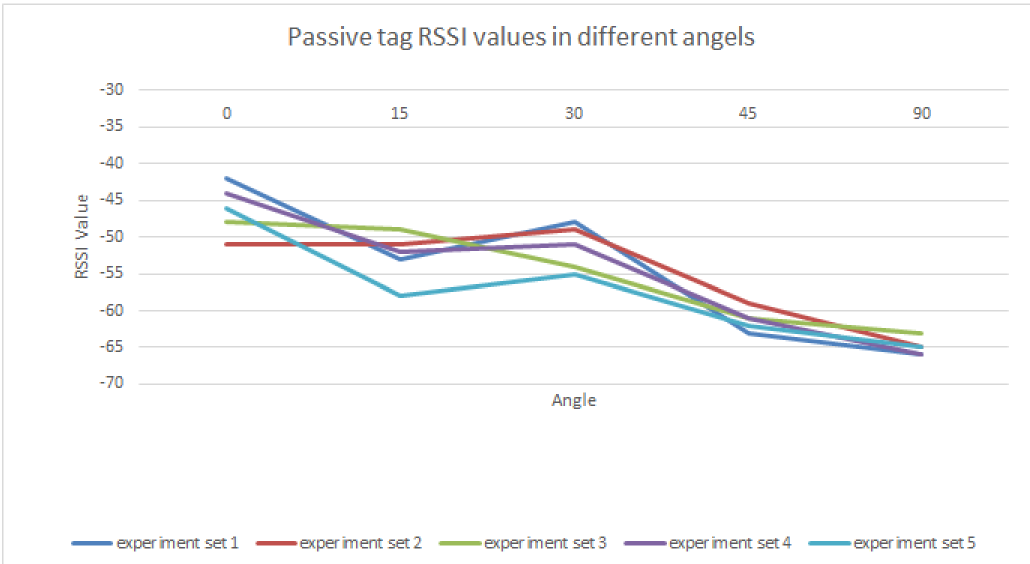


Figure 5.4: RSSI values for different angles between the reader antenna and UHF tag

Antenna orientation

For this experiment we put a passive UHF tag 2m away from the reader antenna. As with previous experiments, the RSSI value reported in the Figure 5.4 is the average of 500 reads for each angle. We changed the angle of UHF tag between "0" to "90" degree with interval of "15" degrees. The results can be seen in Figure 5.4.

According to our experiments with different type of tags, depending on the model of chipset and antenna design of the UHF tag, the RSSI values at each angle can be different. This is one of the significant problems with localization based on RSSI value of UHF passive tags. Because the tags are attached to mobile objects, the angle of the UHF tags to the antenna will vary, making it more difficult to estimate the distance between the tag and the reader and increasing the mean square error.

5.2.2 Reader and ST test

The same 3 factors as discussed above are important for the ST and reader. The only difference is the RSSI value of ST is much stronger than that of the UHF passive tag, because it is designed as semi-passive tag. The experiments with ST have been done with a 9 V 1800mAh Alkaline battery and the antenna attached to the ST is an omni-directional antenna with 3dbi gain. Figure 5.5 and Figure 5.6 show the measured values for the same experiment that has been done for the passive tag in the previous subsection.

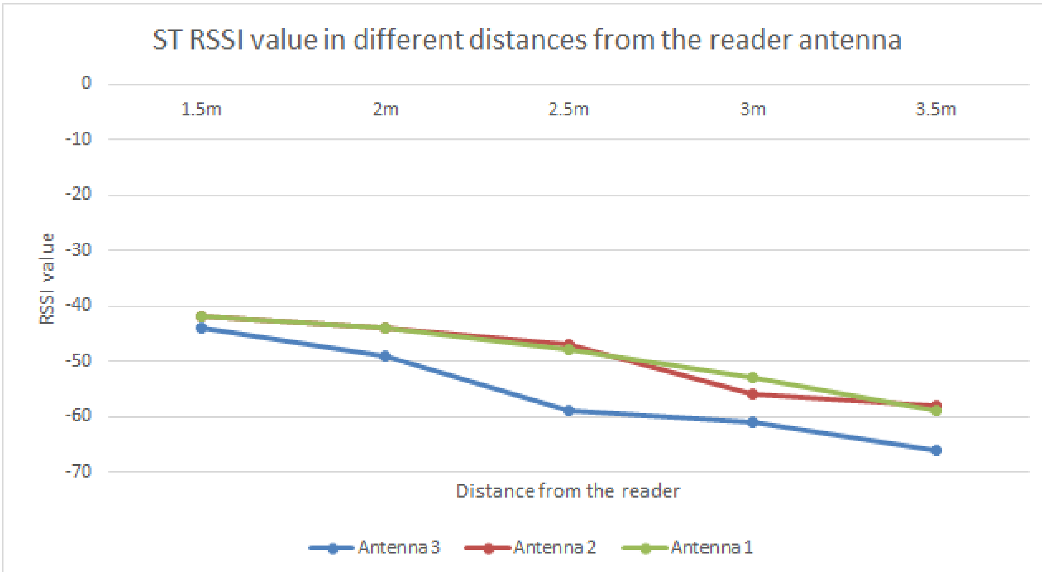


Figure 5.5: RSSI values for different distances between the reader antenna and ST

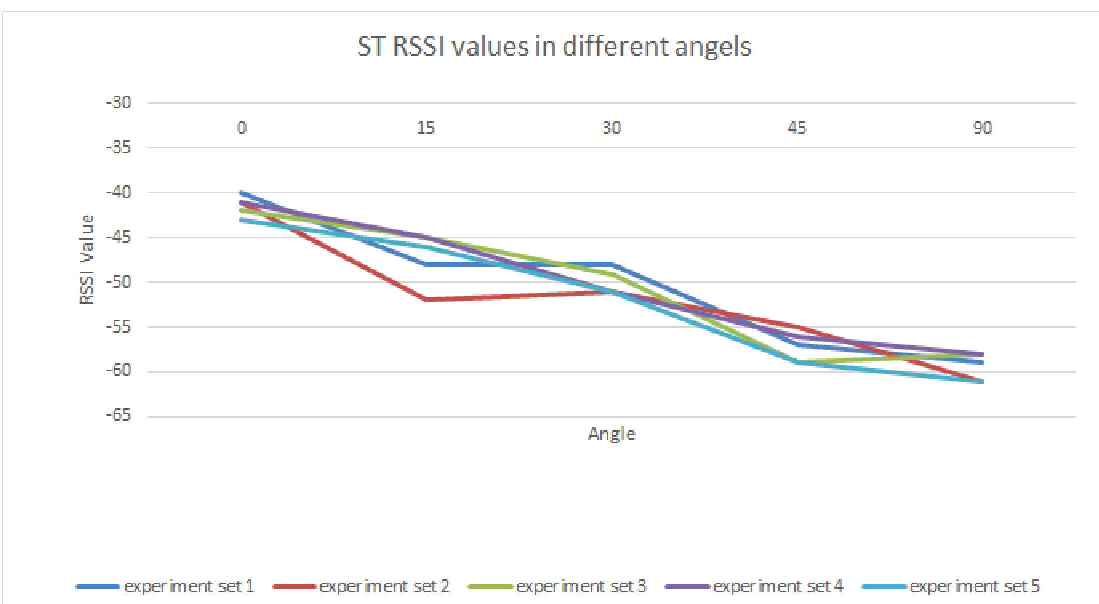


Figure 5.6: RSSI values for different angles between the reader antenna and ST

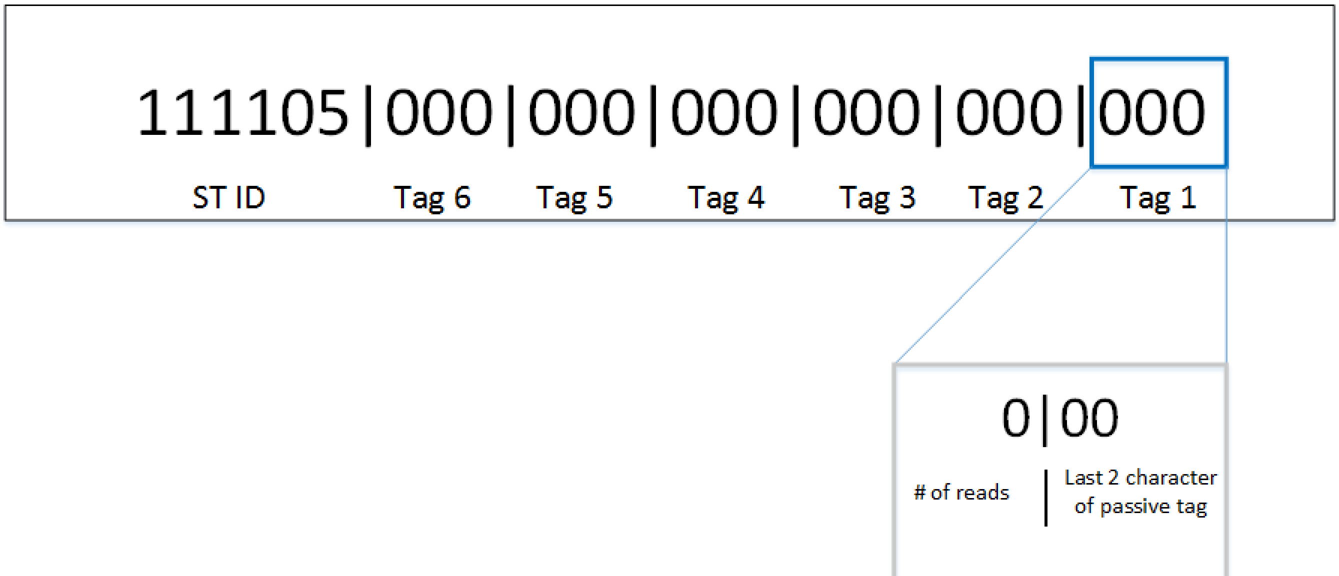


Figure 5.7: ST EPC structure

5.2.3 ST and tag test

This experiment shows the factors that affect the reading of tags by ST. We can consider the ST as a reader in this situation, so the same factors between reader and tags are valid here too. An additional factor is being added - the human body, because we are going to use ST for human tracking in the IoT.

In ST side, we do not have access to the RSSI value. Instead, number of reads are the factor that we consider for detection. ST can report 6 EPCs on vicinity per each report. Figure 5.7 shows the structure of reported message(EPC) by ST to the reader. Each 3 byte from right belongs to the information of one passive tag in the vicinity. The first two characters are the last 2 character of a passive tag's EPC and the third character is the number of reads from previous the report to the current one, starting from "0". This means that a "0" in the third character indicates 1 read. The maximum number of reads that can be reported on each round is "F" or "15". The ST reports its stored information by receiving a special command from the reader. A parameter called a "Locator round" has been set in the software. This variable determines how often the command for receiving the information from ST, has to be sent by the reader. The locator round parameter cannot be greater than 15, since an ST can only report up to 15 reads per round.

Based on our experiments with humans, doing activities at their natural pace we found the best value for the locator round parameter to be "5".

Three factors in terms of distance are important to the ST read range. The first is the distance from reader to ST. The second is the distance from the reader and the tag. The third is the distance from ST to the tag. We note that the human body changes the antenna parameters of the ST, affecting its input impedance, radiation pattern and antenna gain [118]. We have done further experiments on these factors to understand the capability of the ST in proximity detection. These results will be explained in detail in the next chapter in section 6.2.

5.3 Software design

5.3.1 Overview

In this section we explain the software developed by us in C# for running the experiment for tracking and localization. We will explain how we read/send the information from/to the reader. How to query the ST and its corresponding command will be discussed in this chapter.

5.3.2 LLRP

The LLRP (Low-Level Reader Protocol) standard [119] is a specification for the interface between RFID readers and clients, such as smart-phones or PCs. Many RFID reader manufacturers use this standard for their reader-client interface [120]. LLRP does not only support the EPC Gen 2 standard, but also provides an interface for the addition of other standards. Using this protocol it is possible to set the reader configuration and the air-protocol configurations. Modulation, encoding, frequency range, Q-value, output power level, and sensitivity are some of the flexibilities that it provides. These settings can be modified to boost performance or to mitigate interference of RFID systems.

In the LLRP, standard messages have been defined and all of the communication between reader and clients are based on these messages. Client-to-Reader messages include capability discovery, managing inventory, getting and setting the configuration of the reader, and accessing the operations. In reverse, messages from Reader-to-Client include RF survey reports, inventory results, status reports, and access results. A parameter can contain one or more fields or messages.

5.3.3 RFID Locator software

5.3.3.1 Software back-end

The goal of this software is to send commands to the reader, receive the information from it using LAN/WLAN and finally process the received data and present it on an interface for the user. We used LLRP for the reader to PC communication and vice versa. The software has to be multi-threaded to be able to show the results in real-time. Therefore, sending the commands, receiving the information from the reader and processing the received data must all be done in parallel.

Impinjreader class in the project runs all the functions related to reader-PC communication including: connecting to reader, setting reader characteristics such as power level, switching between antennas, receiving the packet from the reader and splitting it down to store them in understandable variables, checking reader status and reporting for debugging the system.

A timer is set in the software to tell the reader to interrogate the zone at specific time intervals. This time will be set by user in the setting. The reader sends a command to the ST by putting a mask on its query once it reaches the value of the "locator round". This value will be checked every time in the timer interrupt. According to this value the reader will be asked to read all the tags or just read the ST information.

The software will store all the received passive tags' EPCs with their corresponding information such as RSSI, time, count and antenna ID. If the EPC belongs to the ST, it splits the EPC to 13 different parts consisting of ST-ID, 6 detected tag IDs in the vicinity and their number of reads in that report. All the variables will be stored for further processes.

Table. 5.1 shows the part of the log file that the software generates based on received ST EPCs.

First column represents Electronic Product Code (EPC) register created by ST and backscattered to the reader. Second column is the time when the measurement is taken. Third and fourth column represent X and Y coordinates of the current position of the ST. In fifth column, we can find the ID of the active antenna, and in sixth column, the reported received signal strength (ST-to-reader RSS).

5.3.3.2 Localization method

The method used for localization using received data is *"Weighted Centroid"*. In pure centroid method the target calculates its position at the center of the positions of the tags that

Table 5.1: Sample ST log file.

EPC	Time in sec	X Position	Y Position	Ant. ID	RSSI
E1111050000000000000005123	0	0,01111111	0,01111111	2	-44
E1111050000000000056023044	0,51765	1,91916901	0,01111111	1	-59
E1111050000000000005156023	1,56273	5,77133389	0,01111111	1	-59
E1111050000000000000156123	3,09678	11,42584219	0,01111111	1	-59
E1111050000000000000000123	4,21535	15,54889121	0,01111111	1	-63
E1111050000000000023156055	5,05575	18,64660561	0,01111111	1	-60
E1111050000000123144156155	6,30523	23,25218889	0,01111111	1	-61
E1111050000000000000005055	6,45834	23,81655235	0,01111111	2	-44
E1111050000000000000000005	7,48528	27,60185319	0,01111111	1	-60
E1111050000000000044023055	8,47986	31,26787507	0,01111111	1	-62

are in the vicinity or are read, as shown in Figure 5.8(a). To increase the accuracy of the localization, *"Weights"* are introduced into this system. Weights are used to calculate the distance of the target from each respective tag, as shown in Figure 5.8(b). Depending on the system, weights can be a function of RSSI value or other factors that can be a representation of distance from each tag. In our case, number of reads by the ST has been used for weight factors.

The only kind of distance information used in centroid localization(CL) is the binary information, whether the unknown object is in the communication range of a tag or not. CL relies on the assumption that each tag has a circular area within which it can be sensed by the ST. In the other words, ST can read those tags when the distance between the ST and the tag is smaller than a specific range. The threshold that has been considered for signal strength in RF front-end of the ST can change this read range.

The algorithm which can be performed on each unknown location of ST is shown in equation 5.1. In this formula, $P_i(x, y)$ indicates the position of unknown object i. The known position of tag j is given by $B_j(x, y)$. The number of tags which are within the communication range of the unknown ST is indicated by m.

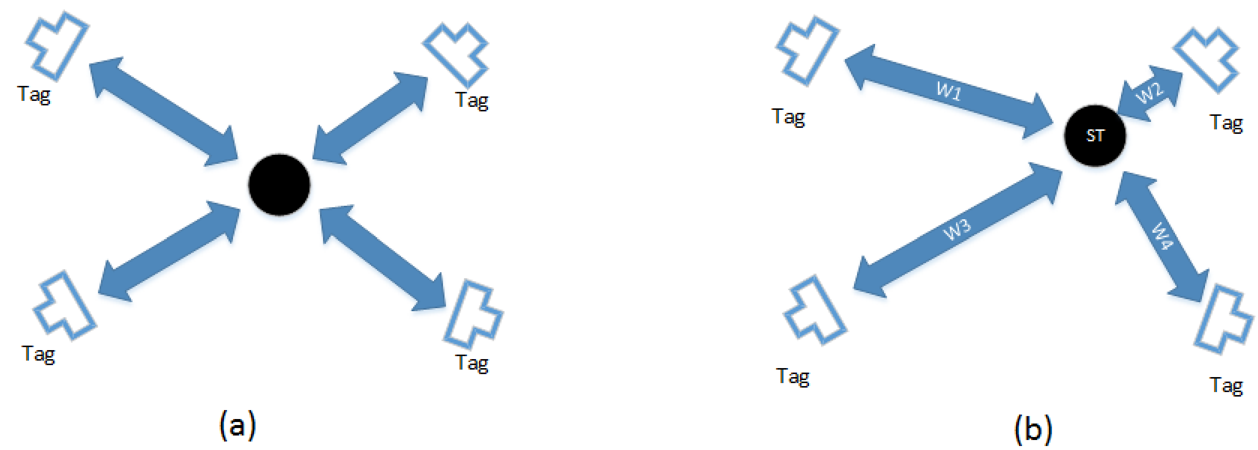


Figure 5.8: (a) Centroid Localization; (b) Weighted Centroid Localization

$$P_i(x, y) = \frac{1}{m} \sum_{j=1}^{n} B_j(x, y) \tag{5.1}$$

Based on CL equation, for example, if an ST is able to communicate to all of the four tags in the vicinity, the software will calculate its position to be in the center of the arrangement (Figure 5.8(a)). Blumenthal et al. showed in [121] that the averaged localization error can not be less than 12% of the Landmark tag distance for CL. This corresponds with the findings published by Bulusu in [55]. Blumenthal et al. also showed that the localization error depends on the ratio between the landmark distance and the communication range.

The low accuracy in location estimation of CL became a motivation for researchers to develop Weighted Centroid Localization (WCL). This method introduced the quantification of the landmarks depending on their distance from the unknown node (ST in our case). The aim is to give more influence to those landmarks which are nearer to the ST. The quantifier (weight) in WCL method is described as shown in equation 5.2, where w_{ij} describes the weight value for landmark j used by receiver i. The distance between landmark j and receiver i is given by d_{ij} and g symbols a degree[122].

$$w_{ij} = \frac{1}{(d_{ij})^g} \tag{5.2}$$

In our system, w_{ij} is the number of tag reads by the ST on each report. That means we put more weight for the landmark tags which are detected more times by the ST. The ST can detect the tags more times if they are closer, because of the stronger backscattered signal. More accuracy can be achieved if we consider the distance between the tags and reader antenna in our weights. We showed in Section 5.2.3 that the number of reads are dependent on the distance between the tag and reader. But for the application of interest in this thesis, the accuracy that we achieve by the number of reads alone, can meet our expectations. Using the weight for the initial equation 5.1, it can be expanded for WCL as shown in equation 5.3.

$$P_i(x,y) = \frac{1}{m}\frac{\sum_{j=1}^{m} w_{ij} \cdot B_j(x,y)}{\sum_{j=1}^{m} w_{ij}} \tag{5.3}$$

$$w_{ij} = \text{Number of the tag reads by the ST on each report} \tag{5.4}$$

5.3.3.3 User interface

The user interface designed for the software uses Windows Form of C#. We tried to make it easy for non-technical users to be able to work with the software. Figure 5.9 shows the look of the software.

In our "select data file" panel, the information of landmark tags and antenna locations will be imported to the software. The landmark information file consists of tags' IDs, their location in XYZ coordinates and RSSI values that were measured for each tag. However, the RSSI value will be updated if it has been changed after starting the query. The antenna information file consists of antenna IDs, their locations in XYZ coordinates and the power transmission level for each antenna.

To start the simulation we connect to the reader first. By clicking on "Setting/Reader" we can choose the reader and set its IP and other settings in the pop-up window. By clicking connect, the status bar reports if the connection has been successful. After successful connection, then we set the settings for querying the zone. This is done on the horizontal menu bar. By clicking on the "locator" in the menu, we will set the locator round, as previously discussed. Note that the software only sends the command to ST if we set the locator round and its label color is "red" during the experiment. "Total query" determines how many queries should be send from the beginning to the end of the experiment. "Query interval" determines the time intervals between each query. Based on our experiment with a Impinj R1000 reader, the minimum secure time interval is 200ms.

"Algorithm" in the menu is the variable that is used for data processing and localization. If algorithm value is "1", then CL will be considered for localization. Changing this value to "2" will apply WCL for localization. By activating "Zone divide", we can switch between

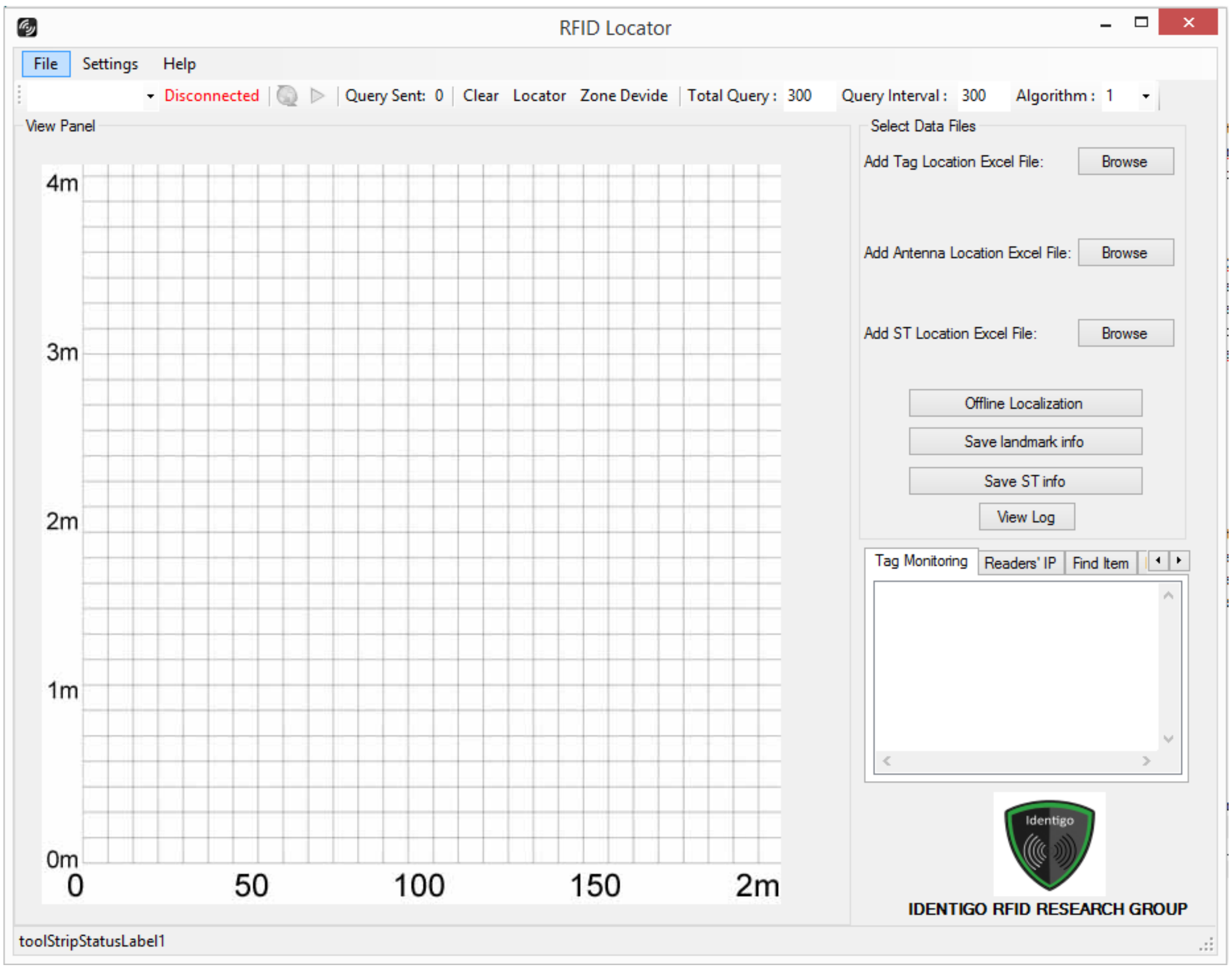


Figure 5.9: User interface of RFID locator software

antennas at specific time interval. Zone divide can sometimes improve the accuracy if we are using multiple antennas in big area.

Figure 5.10 illustrates the software after the setup once the "Run" button has been clicked. First the software arranges the landmark tags, based on their information. Then it checks the RSSI value backscattered from each landmark and updates the values for RSSI. Red dots in the zone represent ST locations on each report. We can see the details of each ST location and their corresponding time, by hovering the mouse on top of each red dot.

Information about all the EPCs that have been read are then saved in Excel file by clicking on the save buttons for landmark and ST information. At a later time, we can load the saved files and experiment offline with other algorithms for localization.

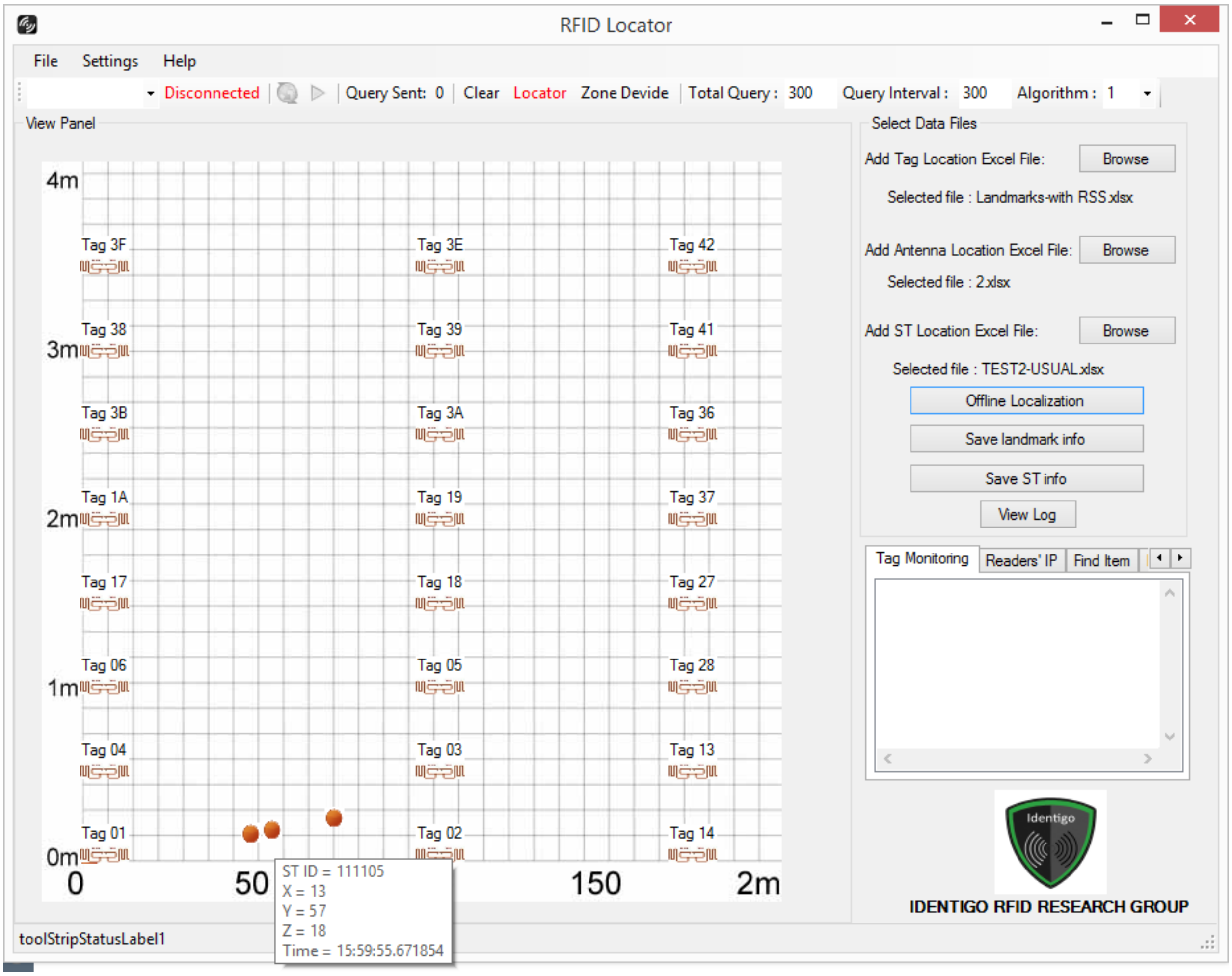


Figure 5.10: User interface of RFID locator software after doing setup and running the localization

Chapter 6

Experiments and Applications

6.1 Overview

This chapter presents the tests that were done based on some IoT applications. We tested the reader, tag and the ST characteristics such as range, read rate, and performance with the tag under different distance and orientations, in realistic environment in previous chapter. We used those information to setup the reader and the landmarks in the lab. Different applications in IoT have been considered to see if ST based RFID system can help in realizing them or not. These applications are proximity detection, localization, portal and cross reading, and activity tracking.

We would like to point out that these experiments are using only the initial prototype of the ST and that we will have better performance results with the next version of the ST.

In all of the experiments the same RFID tags and reader in previous chapter have been used. In addition, we used our ST with an antenna with the gain of 3 dBi.

Bellow, we will explain each one including the experiment results and factors that are important for each experiment.

6.2 Proximity Detection

6.2.1 Object-to-object interactions when the objects are stationary

The goal of this experiment was to determine the proximity range between an ST and a tag for different distances between the ST and the reader antenna. The purpose of the experiment was to show that the ST is suitable for detecting interactions among objects as well as to point out limitations. The experimental setup was the following. The ST was attached to a wooden object, and four UHF tags were placed on a paper box. The distance between the ST and the reader antenna was changed from 1.5 m to 5 m. The tags were placed behind the ST so that the ST was between the tags and the reader antenna. We recorded the number of times the ST detected the tag during a 1 minute period. For every distance between the reader and the ST, we changed the distance between the tags and the ST until the ST was able to detect the tags about 200 times during 1 min. The distance between the tags and the ST and the ST detection rate are shown in the first and third column of Table 6.1.

From the results, we conclude the proximity detection range for fixed detection rate depends on the distance between the ST and the reader. This is an expected result because the ST detects backscattered signal from the tag and when the tag is farther from the reader, the ST needs to be closer to the tag to receive the same power level. This feature needs to be taken into account when using STs for IoT applications.

Table 6.1: Detection rate for different distances between the ST and the reader and the ST and the tag when both the tag and the ST are stationary and the tag is placed either on an object or on a person.

Number of times the ST attached on the object detects a tag		**Distance between tag and ST**	**Distance between ST and reader**
Tag on another object	***Tag on the human body***		
246	84	130 cm	150 cm
152	34	130 cm	300 cm
228	75	45 cm	300 cm
192	14	45 cm	500 cm
216	43	30 cm	500 cm

6.2.2 Object-to-person interaction when both are stationary

The goal of this experiment was to determine the proximity range between the ST that is on an object and the tag that is placed near a human body (on the chest). The purpose of the experiment was to evaluate the suitability of using STs for detecting interaction between objects and people.

We performed the experiment with the same distances as defined in the previous experiment. For these distances, we collected the number of times the ST detected the tag. The detection rates are shown in the second column of Table 6.1. We note that the human body detunes the antenna of the tag by affecting its parameters such as the input impedance, radiation pattern and antenna gain. In view of this and since considerable part of the reader signal is absorbed by the human body, the detection rate of the ST is reduced. If we compare the detection rates presented in the first and second columns of Table 6.1, we see that the detection rate decreased four times on average when the tag was near the human body in comparison to the setup when both the tag and the ST were attached to objects. Note that we used the same tag for all the experiments and did not use a tag that is specially designed to operate in the proximity of a human body. The reason was that that we wanted to achieve consistency among the experiments.

6.2.3 Object-to-object interactions when one object is mobile

1) The ST is attached to a mobile object and a tag to a stationary object

The goal of this experiment was to determine when the ST can be detected as it approached a stationary tag. The purpose of the experiment was to show how the detection rate increases as the ST is coming closer to the stationary tag. The application is detection of proximity of mobile objects. The experimental setup was the following. An ST was placed on a robot and a UHF tag on an object. When the robot moved, the ST's antenna was parallel to both the tag's and reader's antennas as shown in Figure 6.1.

The distance between the reader's antenna and the ST was 2 m and between the tag and the ST, 0.9 m when the angle was 0 degree. The ST started at the angle of about 70 degrees between the stationary tag and the ST. During the robot's movement, the distance between the ST and the reader was changing together with the distance between the tag and the ST and the angle between the ST and the tag. We partitioned the half plane on one side of the robot's track by radial lines, where the angle between the lines was 15 degrees, as shown in Figure 6.2. The figure shows the reader's antenna (the white antenna on the left), the tag placed on a wooden pole (in the middle) and the robot with the ST that moves on track shown in black. The radial lines are in yellow color and they form segments on the track of

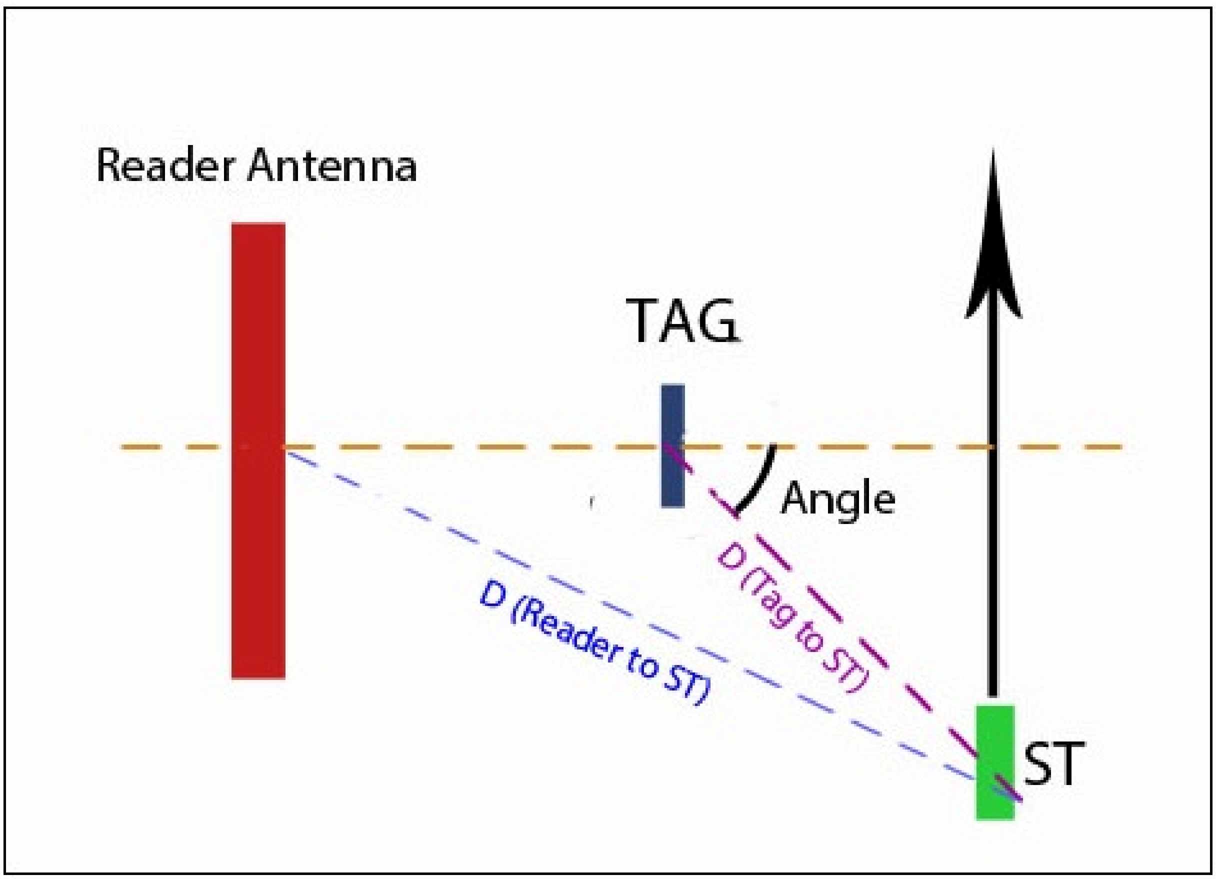


Figure 6.1: A mobile ST and stationary tag experiment.

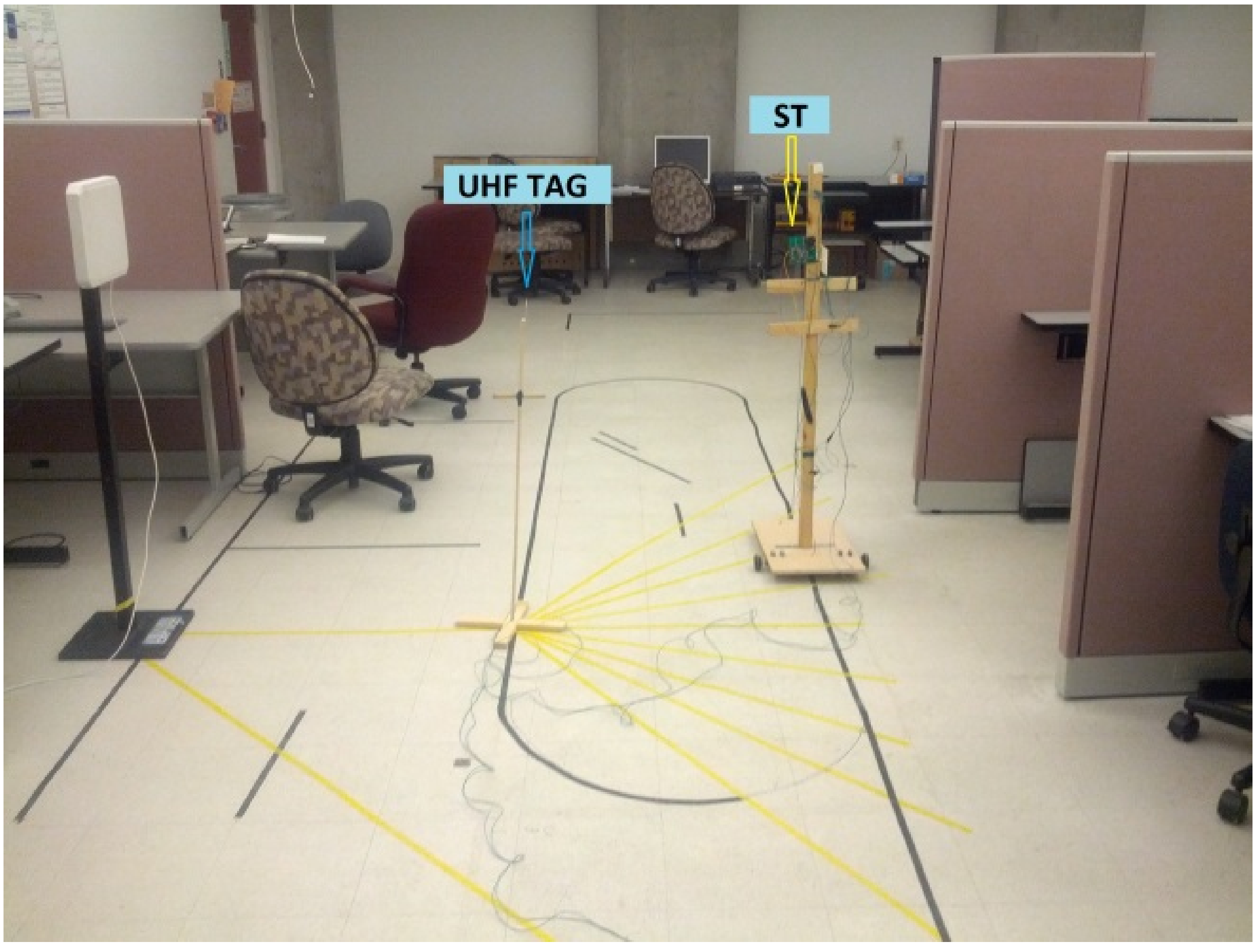


Figure 6.2: The experimental setup.

the robot. We recorded the detection rate of the ST for each segment.

The results of the experiments are shown in Figure 6.3. The figure displays the number of times the ST detected the tag for each segment for three different speeds of the robot: 3.6 cm/sec, 5.4 cm/sec and 8.2 cm/sec. The results show that an incoming ST is detected when it is at an angle 60 degrees relative to the tag and that the detection rate improves as the ST approaches the tag. Also, the detection rate decreases as the speed increases because the ST spends less time in the field of the reader.

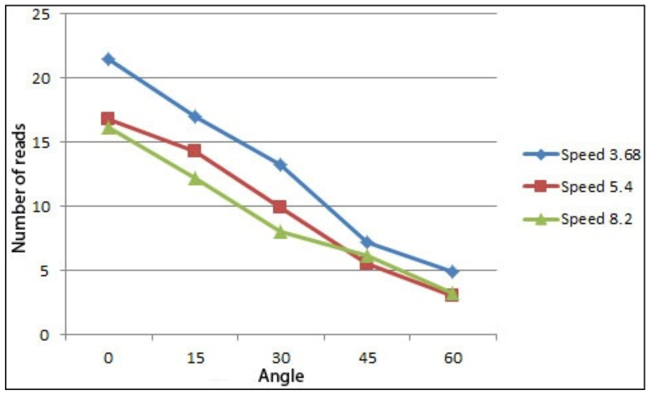


Figure 6.3: The number of times a tag is detected by a mobile ST when the ST is in the segment corresponding to angles of 0, 15, 30, 45 and 60 degrees, respectively, and for three different speeds of the robot.

2) A tag is attached to a mobile objects and an ST to a stationary object

This experiment is similar to the previous one except that the tag is now attached to a mobile robot and the ST is stationary. The results are shown in Figure 6.4. The detection rate is lower than the detection rate in the previous experiment (Figure 6.3). This result shows that the distance between a tag and a reader, which changes the strength of the tag's backscattered signal, is more important than the position of the ST in the proximity circle of the tag with the same angle.

6.3 Localization

6.3.1 Locating stationary objects

The goal of this experiment was to determine whether it is possible to locate a tagged object in an indoor area. The software described in section 5.3 has been used to localize the ST in landmarked area. Locator round variable has been set to "5". That means the ST listen to the tags in five query rounds, then transmits its information to the reader after modifying its EPC.

The position of the ST was estimated by the weighted centroid method. Figure 6.5 shows the localization for two different locations in the area. Two hundred samples recorded from the ST in 20 seconds. Each red dot in the picture represents one location based on its

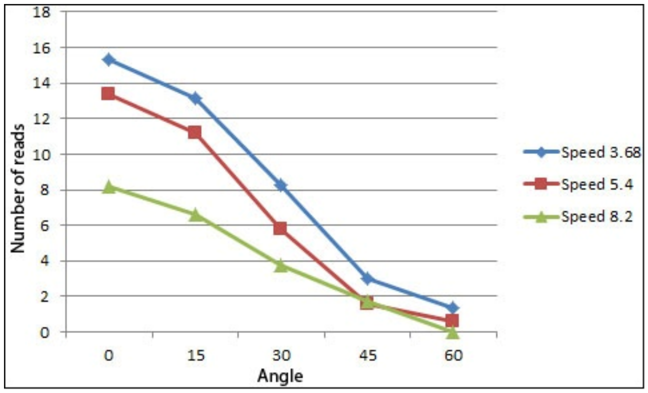


Figure 6.4: Number of times a mobile tag is detected by a stationary ST when the tag is in the segment corresponding to angles of 0, 15, 30, 45 and 60 degrees, respectively, and for three different speeds of the robot.

corresponding report. The actual location for Figure 6.5 (a) is (50cm,200cm) and for Figure 6.5 (b) is (50cm,350cm). We used one RFID reader with one antenna placed at (1 m, 3.5 m). The height of the antenna was 2.6 m.

We can see in Figure 6.5 that the accuracy of localization is dependent on the position of the reader antenna relative to the position of the ST. The reasons for non-consistency of accuracy is that in different locations, the distance, angle and RSSI value of both tag and ST changes. Table. 6.2 shows 20 randomly chosen records out of 200 for Figure 6.5. The average error in Figure 6.5 (a) is 19.5cm in X coordinate and 24.3cm in Y coordinate. These values drop down to 12.8cm in X and 22.1 in Y in Figure 6.5 (b).

The same experiment applied in 50 different locations in the zone. The average error in localizing stationary objects based on 20,000 records is 12cm in X(vertical direction) and 21cm in Y(horizontal direction). The reason for the difference in mean square error in different coordinates is that we have more symmetric landmark placement in X which leads to same weight for negative and positive side of the location.

6.3.2 Locating mobile objects

The goal of this experiment was to determine whether it is possible to locate a moving object in an indoor area. The area was 4 m x 2 m and was covered with passive UHF RFID landmark tags. Landmark points have been considered every 0.5m in X axis in 3 different rows in distance of 1m (Figure 6.6 (a)). In the experiment we used a robot that was tagged with an ST and was moving along a trajectory (Figure 6.6 (b)). Three passive tag placed in

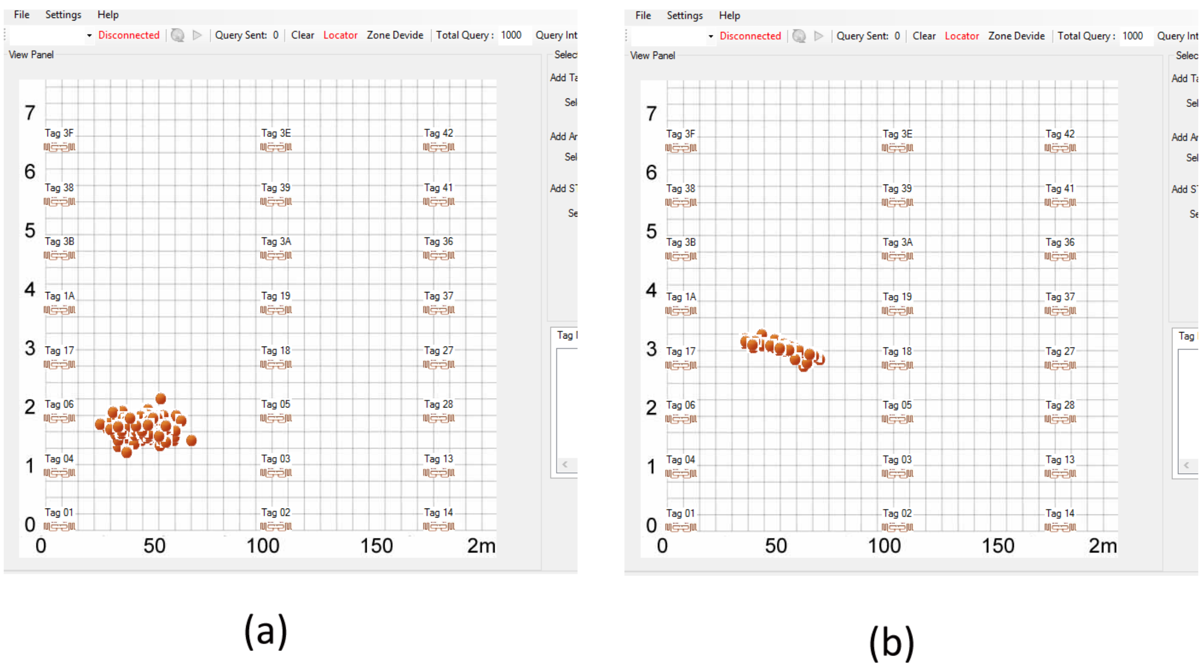
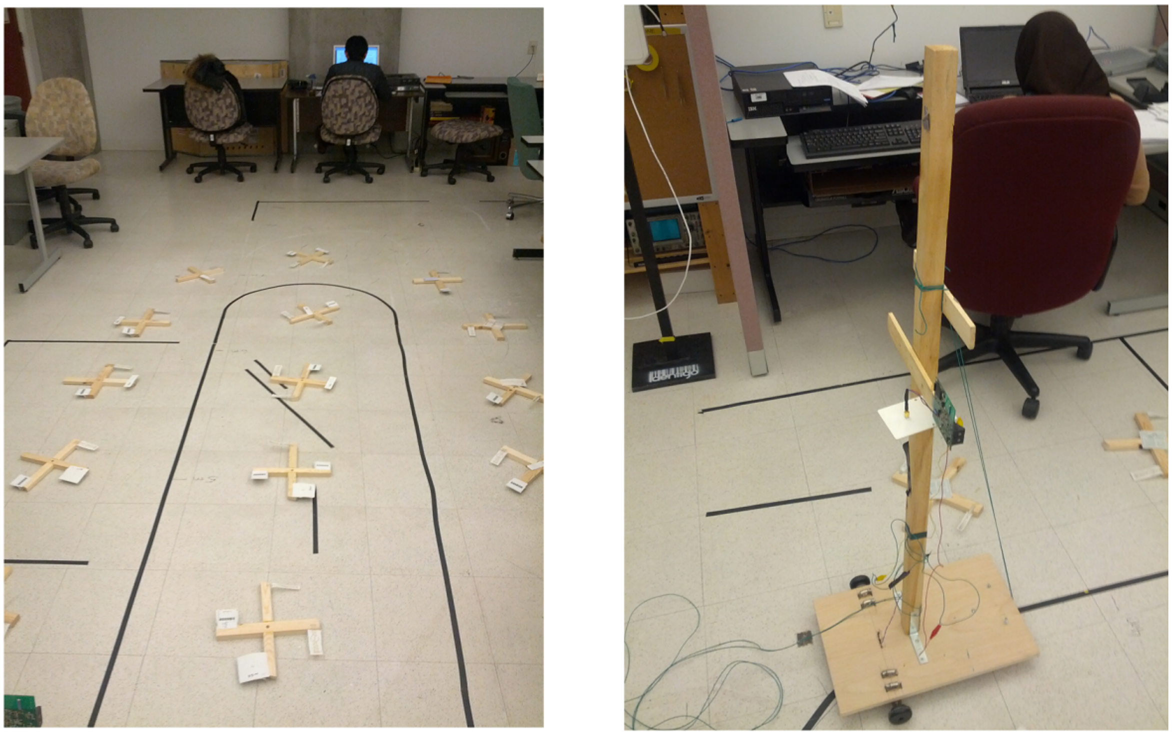


Figure 6.5: Location estimation for two different locations in landmarked area. (a) Location(50cm,200cm). (b) Location(50cm,350cm).

Table 6.2: Twenty records out of 200 for Figure 6.5 (a) and errors(cm) in each coordinate

EPC	RSSI	STY	STX	Error in Y	Error in X
1111051153281193063 3C227	-50	85	169	35	31
1111052361191293123 2623C	-55	89	186	39	14
11110501913C21203A13B326	-51	69	188	19	12
1111050360371182263 3C03B	-53	79	200	29	0
11110513721723C03B118226	-51	76	185	26	15
11110531811723C029326136	-55	96	187	46	13
1111052171182123262 3633C	-49	72	178	22	22
1111051121373181262 1933C	-51	72	176	22	24
11110521A21233C13B126118	-56	67	181	17	19
11110503A23B33C31232601A	-53	88	188	38	12
11110521933C11833A217312	-51	80	177	30	23
11110511212623C113236017	-50	101	169	51	31
11110523C136213129326117	-54	60	171	10	29
11110511922911233C01A137	-54	85	185	35	15
11110521203B33C13A028226	-56	81	182	31	18
1111051371182291362 2623C	-55	85	200	35	0
1111052264181360130 1733C	-54	96	178	46	22
11110531243A23C226118119	-56	101	186	51	14
1111053123261190293 3C318	-55	70	168	20	32



(a) (b)

Figure 6.6: The experimental setup for direct localization of ST.

each landmark point in order to increase the chance of being read by the ST. The location of the ST was estimated by the WCL method.

In the experiment, tags are located on the floor, ST is 75 cm above the ground and reader antenna location is (1 m, 2 m). The height of the reader antenna was 2.6 m. Figure 6.7 shows the graphical user interface of the software developed for real-time localization. Each red dot is representation of location of the robot. In real-time mode, one red dot adds to the screen if the reader receive the information from the ST. The black line is the actual path of the robot. Most of the calculated locations are closer to the middle column of landmarks. The reason is that the density of landmark tags on the side which is closer to middle line is more than the other side. So the probability of detecting the landmark tags on the more dense side, is higher than the other.

The accuracy of the localization is dependent to the density of landmark tags. We repeated the same experiment with the only difference of reducing number of landmarks to

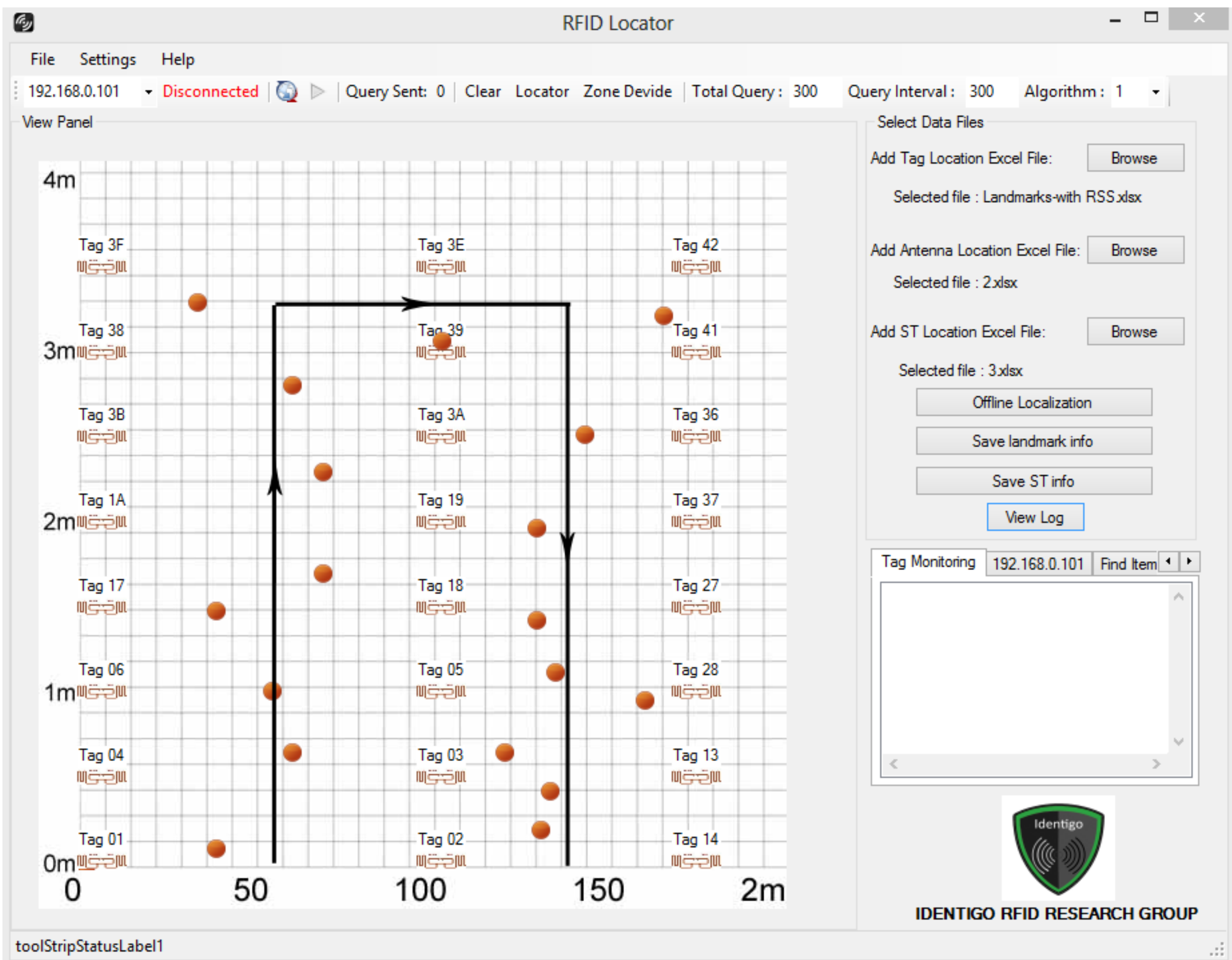


Figure 6.7: Graphical user interface in real-time direct localization. Each location estimation of the ST has been presented by a red dot.

half. In new set of experiment we have landmark tags in every 1m on X direction. Table. 6.3 compare the error in localization between two experiments. For X equals to 100 and 150, the error difference between the two experiment is almost zero. Because the antenna has the maximum power in that area and backscattered signal from the tags are strong, so even with less dense landmark, we have enough reads from each tag.

Table 6.3: Error values for experiment 1 and 2 at different distances from the origin

Distance from the origin	**50**	**100**	**150**	**200**	**250**	**300**	**350**
Error in experiment 1 (cm)	18	15.6	9.2	14	18	16	29
Error in experiment 2 (cm)	28	21.2	11	13	19	29	48

Figure 6.8 shows the relation between the real location and calculated location in 5 sets of experiments. Each dot is a representation of one location report from the ST. According to the Figure 6.8 we can conclude that the average error can be approximated using a linear function and the relation between the real value and calculated value can be presented by a linear equation (diagonal line in Figure 6.8). Equation 6.1 describes the relation between real and calculated value in our experiment. Note that the equation for the error can be different in other environments, but follows the same behavior.

$$Y_{real} = 1.275 \cdot Y_{est} - 56.031 \tag{6.1}$$

6.3.3 Locating mobile objects and indirect locating stationary tags

The goal of this experiment was to determine whether it is possible to locate a moving object that carries an ST as well as to indirectly locate static objects tagged with passive tags. In the experiment we used a robot that was tagged with an ST and was moving along a trajectory. The area was 4 m x 2 m and was covered with passive UHF RFID landmark tags. Software was developed in C# has been used to process the received data from the ST, to control the reader and to log the activity (Figure 6.9). The position of the ST was estimated by the WCL method.

In the experiment, we had 24 landmark tags. Two boxes with UHF passive tags were in the area with coordinates BOX1 (100,125) and BOX2 (100,300). We used one RFID reader with one antenna placed at (1 m, 2 m). The height of the antenna was 2.6 m. We performed additional experiments where, first, 10 more tags were added to the environment and then

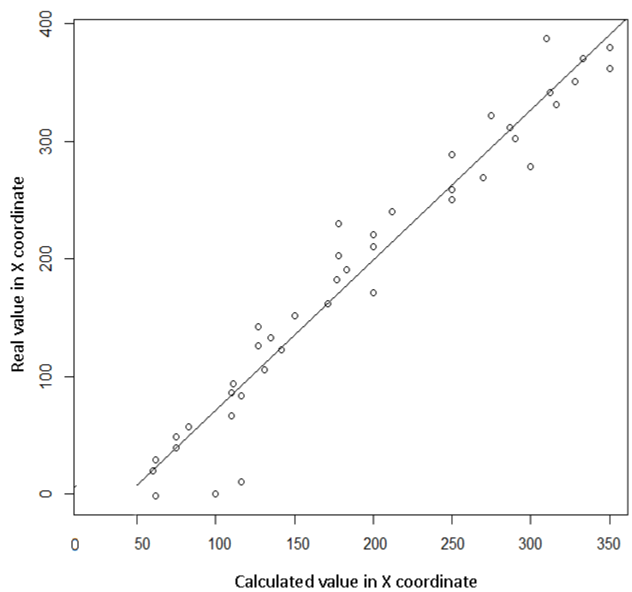


Figure 6.8: Estimated location and their corresponding real location in direct localization.

when two persons were standing between the boxes and the moving robot. The estimate of the location of the ST is presented on the screen using red dots. The green circles represent the position estimates of BOX1, and the blue circles the position estimates of BOX2. The accuracy of the system in estimating the ST's location was better than 32 cm in the X direction. Note that the reader antenna is placed in the middle and the number of landmark tags at the beginning and at the end of the path is smaller and therefore the localization error is different throughout the path.

The second part of the experiment for determining if it is possible to locate the positions of unknown tags based on the estimated position of the ST showed that when an ST was close to a tagged box, the boxes were detected and located. The ST detected boxes all repetition of experiments and in all the cases. It reported approximately every second but did not detect the boxes in each report. The number of reports when the STs were in the range of the boxes was between 40% and 66%, which was enough to detect boxes every time. The proximity of people or other tags did not affect neither the localization performance nor the detection and localization of the boxes. In a similar way, we can design a system to track people carrying STs and determine if they carry tagged objects. This can be used to identify in real time if someone moves and carries important, dangerous, expensive or other

Figure 6.9: Graphical User Interface of the software for localization of STs in real-time.

objects.

6.4 Activity Tracking

6.4.1 ST as a wearable device

The purpose of the experiment was to demonstrate that the ST is suitable for tracking daily interactions of people and objects. In this experiment, we investigated if it is feasible to detect that a person is moving a tagged object. We attached UHF tags with the Philips "MF1S70" chip to several boxes. To improve the performance of the system, each item was

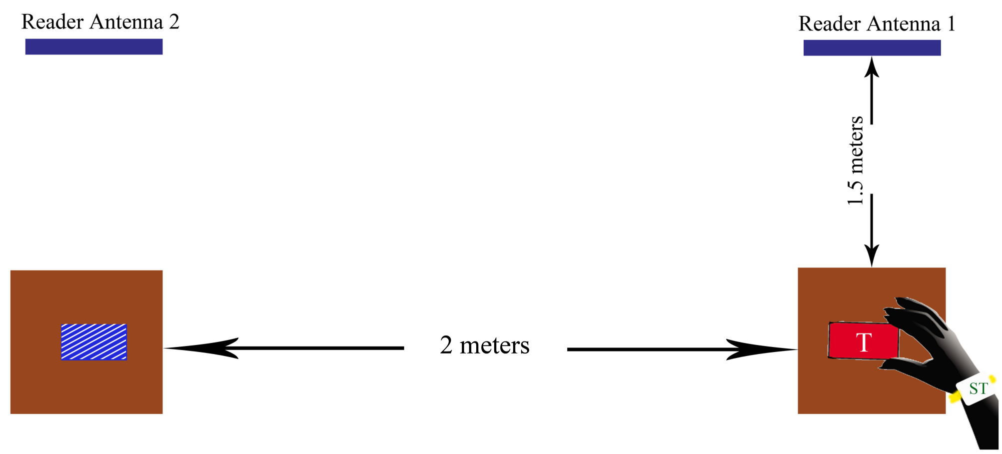


Figure 6.10: An experimental setup for tracking interactions between a person and an object.

tagged by two tags placed on the top and on the side of the object. An ST was used as a wristband worn by the person.

The experimental setup is shown in Figure 6.10. The person who wore the ST was getting close to the object placed on the right desk, grabbed the object, and put it on the left desk. The distance between the desks was 2 m. The reader antennas were separated by 1.5 m and placed in front of each desk. The reader switched between the antennas every second. The UHF tags on the boxes could be read by both reader antennas so that it was not easy to detect the movement without STs. The number of reads of the tags on the object of interest by reader antennas 1 and 2 is presented in Figure 6.11 by yellow line for the reader antenna 1 and blue for antenna 2. Number of reads by the ST is presented by black line when reader antenna 1 is on and orange when reader antenna 2 is on and finally the grey line represents the total number of ST reads.

We are mainly interested in the number of time the ST detected the tag (gray line on Figure 6.11) and we consider that the person is interacting with the object when the number of ST detections is more than one per second. Therefore, for the current scenario we are always able to detect that there is an interaction between the person and the object.

When the person picked up the item from the right desk, the ST detected the tag only

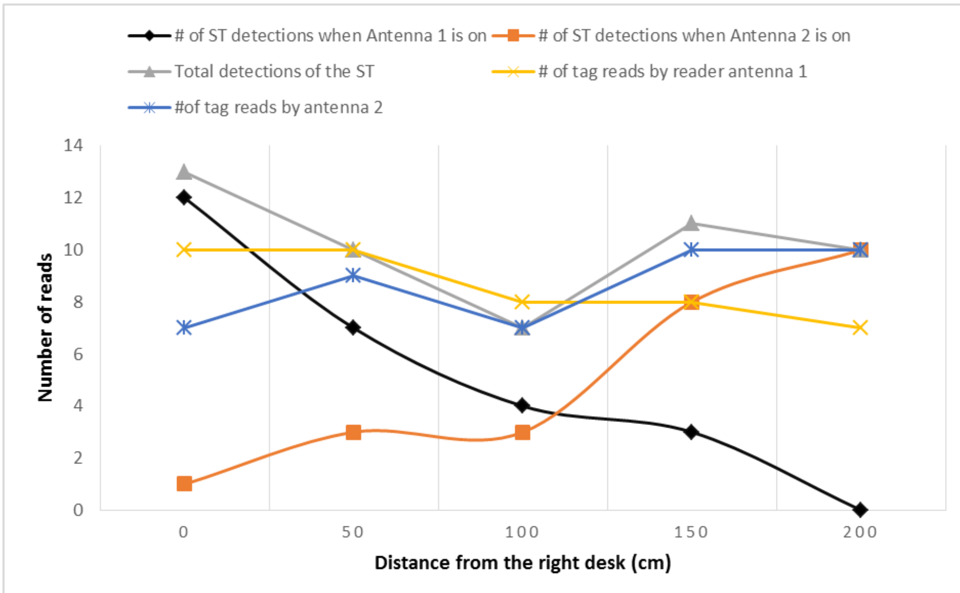


Figure 6.11: Number of reads of a tag by the reader and by the ST in tracking experiment 1.

when the reader antenna 1 was on. About 2 m away from the right desk, the number of ST detections of the tag when antenna 1 was turned on was very small but the number of detections when antenna 2 was turned on was large. The results suggest that the ST allows for the possibility of detecting movement of a tagged object from one desk to another.

The experiment was repeated for the following situations: (a) with a human body between the reader antenna and the ST/tags, (b) with 10 other tags on different objects, and (c) with only one tag attached on the tracked object. In case (a) the system was not reliable. We believe that the reason is the drop in performance of the ST in the proximity of human body and the reduced power of the backscattered signal of the tag caused by the human body. Other tags (Experiment (b)) did not affect the performance. The number of times the tag was detected by the ST dropped more than three times when only one tag was used (Experiment (c)) and therefore it is possible to use this system with one tag per object. We aim at improving the ST so that it is less sensitive to settings like in (a) and (c).

In the second experiment, we picked a tagged object up from the desk 1 and moved it half way and returned it back. The goal of the experiment was to see if the ST can provide better result for estimating the type of movement compare to non-ST-based RFID system. As shown in Figure 6.12, number of reads start to decrease for antenna #1 and then increase again. Exactly the opposite behavior can be seen for antenna #2. Since the number of reads

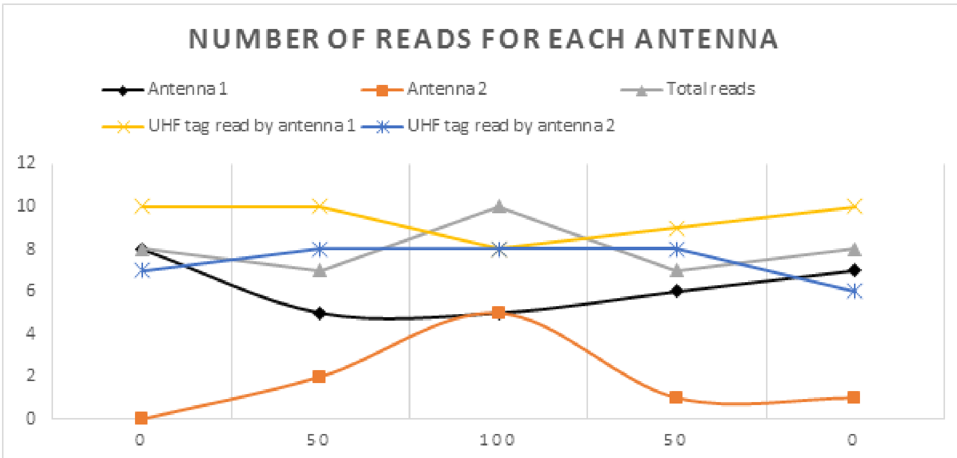


Figure 6.12: Number of reads of a tag by the reader and by the ST in tracking experiment 2.

in the reader side for passive tags is almost the same in its interrogation zone read range, it is hard to estimate the type of tracking by considering just number of passive tags (see yellow and blue line in Figure 6.11 and Figure 6.12. But by considering the number of reads by ST, we can estimate that the object got close/away to/from antenna 2/1 and again got away/close from/to it.

6.4.2 Passive tag as a wearable device

In this experiment, we tracked interaction between a person and an object. We attached a ST to a paper box and used a UHF tag as a wristband. This experiment presents the opposite situation from the one presented in the previous subsection where the ST was attached to a person and the tag to an object. Again, we used the same type of tag as in the previous experiments for consistency reasons and not a commercial wristband tag. The tag was separated from the arm by an isolator that is about 0.8 cm thick. The person who wore the tag is getting close to the box, grabs it and put on another place as shown in Figure 6.13. The distance between the box and reader antenna is 1.5 m and it increases to 2 m after moving the box.

Since the path of the hand's movement is not always the same, we ran the experiment many times. Because of the effect of the human body, the backscattered signal from the tag is weaker than in the experiments that do not involve humans. So the ST starts detecting the tag at 20 cm distance between the tag and the ST. When the distance between the tag and

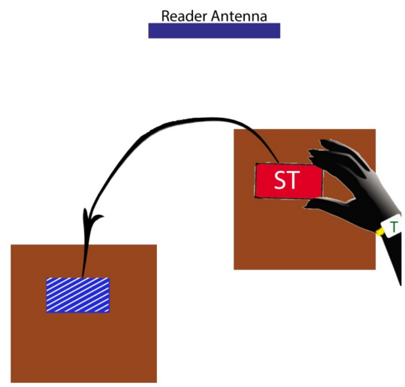


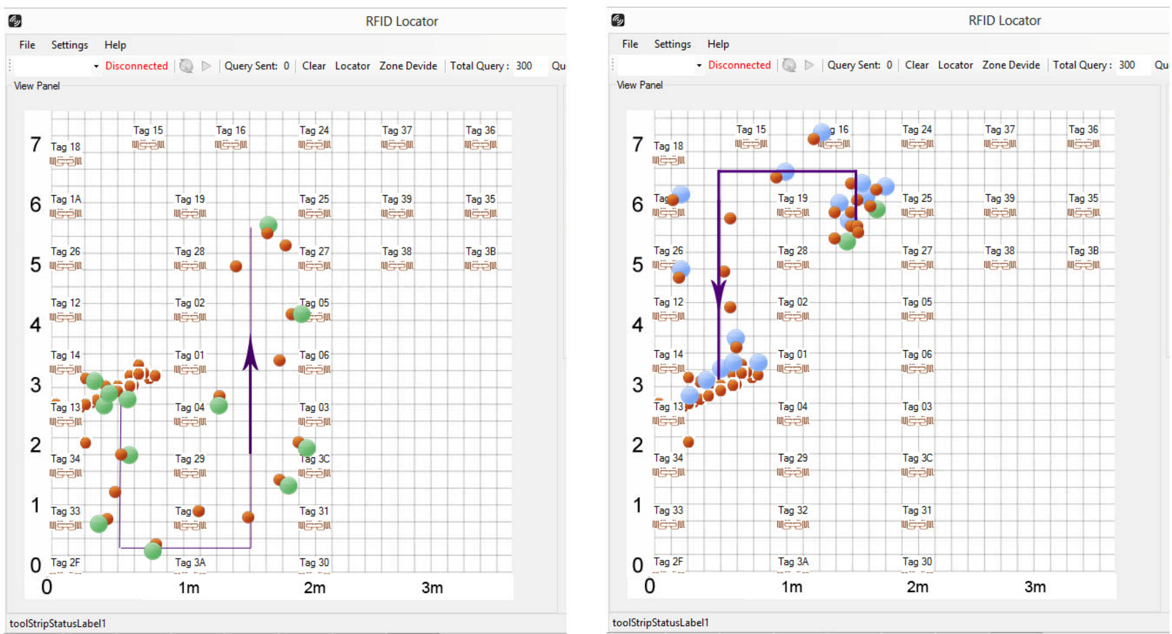
Figure 6.13: Experimental setup for tracking the interactions among a person and an object.

the ST is less than 15 cm, the tag will always be recognized by the ST. In our experiment, the total time required for the movement of the object is about 3 sec while the ST detects a tag approximately 0.5 sec before and after the interaction. In this period of time, the ST can detect the tag on the wrist about 12 times on average. Very different results are obtained depending on whether the tag is directly seen by the reader antenna or if there is an arm in between the reader antenna and the tag. Without the line of sight, the detection rate is only 2 on average. The reason for this is that without the line of sight the tag receives less power and the backscattered power is too low for the ST to detect the tag.

6.4.3 Detecting and locating movement of objects and people in landmarked area

The goal of this experiment was to determine whether the ST is suitable for detecting association between an object with the ST and a tagged person and if it is feasible to track both of them as the person is carrying the object. The purpose of the experiment was to show that the ST is suitable for tracking objects and people in real environment such as a depot or a warehouse.

In this experiment, an object of interest is tagged with the ST. The area is covered using passive UHF RFID landmark tags. Software has been developed in C# used to process the received data from ST, control the reader and log the activity. The user interface is shown in Figure 6.14. The area is 8 m x 4 m and it is covered by 30 landmark tags (it is not completely covered). The one reader with two antennas placed at the following (1.8 m, 5.7 m) and (1.65 m, 2.1 m) is used. The height of the antennas is 2.4 m. The estimate of the



(a) (b)

Figure 6.14: Tracking activity in UHF landmarked area.

location of the ST is presented on the screen using a red dot. As can be seen in the Figure 6.14 (a), the system keeps estimating the position of the sensatag using the WCL method and presenting its position.

Next, two persons with UHF semi-passive wristbands enter the area (EM4325 UHF RFID tag chip). First, one person takes the object with the ST and caries it by following trajectory shown using a light blue line in Figure 6.14 (a). The estimated position of the first person is shown using green dots in Figure 6.14 (a). After this, the first person leaves the box and the second person takes it and carries it to its original place. The real trajectory of the second person is presented using a dark blue line in Figure 6.14 (b) and the estimated positions of the second person using light-blue dots. In both Figure 6.14 (a) and (b) we can see that the system is able to associate the person with the box a number of times. This is shown in the figure when a red circle (the ST) is very close to the green or light-blue circle (people). In this way, we can design a system that can detect in real time who is moving or carrying important, dangerous or expensive objects and where.

This experiment shows that when ST is reporting persons tag ID, localization is less

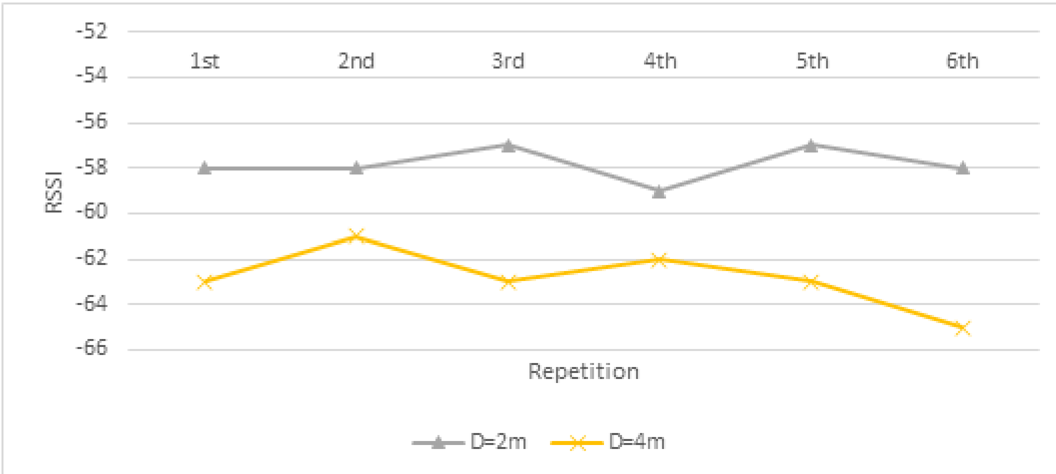


Figure 6.15: LOS experiment for traditional RFID system: RSSI for two different distances between the reader antenna and the tag where measurement is repeated 6 times.

accurate since person‘s ID is replacing with one of landmark IDs, because ST can report just six tags in its vicinity in each report. Also we can see in Figure 6.14 that sometimes the proximity of person is not reported by the ST. However, this is due to current implementation of the ST and can be overcome by decreasing the time interval in sending the ST report and introducing additional logic for detecting association between the ST and the personal tags.

6.5 Non-line-of-sight effects

In this experiment, we show the effect of NLOS on measured RSS values as well as on the performance of the ST. In the first experiment, we recorded the RSS value of a passive tag placed 2 m and 4 m away from the reader. Then we repeated the same experiment with the only difference of presence of a human between the reader and the tag. Figure 6.15 shows the LOS experiment where 6 RSS value were collected at the reader side from a passive tag placed at the distance of 2 m and 4 m. In Figure 6.16, a person enters the zone and stays in the middle between the reader and the tag (d=1 m when tag and the reader are 2 m apart, and d=2 m when the tag and the reader are 4 m apart). In presence of a human, the recorded RSSI values are weaker as expected. The bigger problem is that the RSS values of a tag at the distance of 4 m is LOS situation is very similar to the RSS value of the tag 2 m away from the reader in NLOS situation. Clearly, making decision based on only RSSI values for localization can be quite inaccurate.

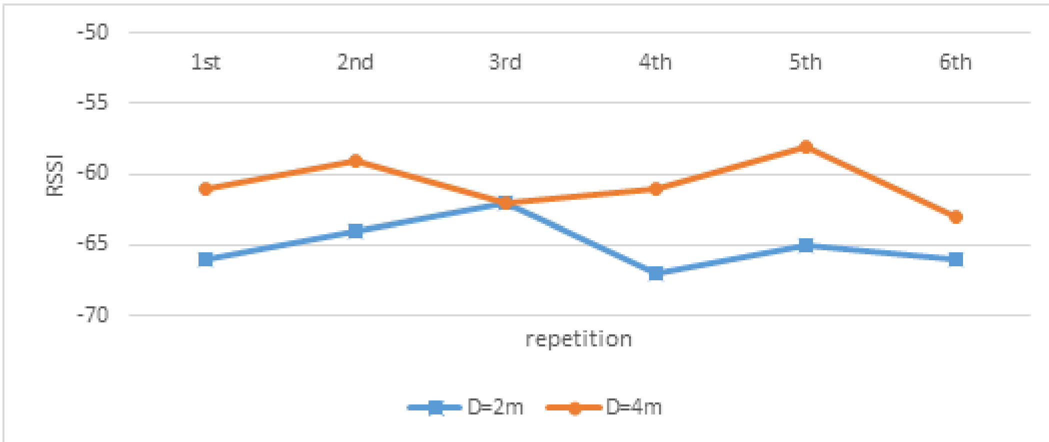


Figure 6.16: NLOS experiment for traditional RFID system: RSSI for two different distances between the reader antenna and the tag where measurement is repeated 6 times.

In the second round of experiments, we placed the ST near the tag at 50 cm distance from the tag and recorded the number of reads by ST in different conditions. Note that for ST-based localization, we just need to detect the presence of the tag in vicinity. So if the number of detections by the ST drops because of the NLOS it does not affect localization performance for as long as the ST can detect the tag signal. Actually, for localization, we need only one detection of the ST. The ST is programmed to listen in 5 query rounds and to report in the sixth so that in this experiment the ST reports the reads every second. Figure 6.17 presents the number of reads in LOS situation when the tag is 2 m and 4 m apart from the reader and the ST is 50 cm from the tag. Figure **??** presents the number of reads for the same setup but for the NLOS situation. Both figures present the total number of reads in 15 seconds.

At 2 m distance between the reader and the tag, the average of number of reads in LOS situation is 3reads/sec. The average of number of reads in NLOS situation is 2.66 reads/sec. Therefore, the ST would work properly for both localization and proximity detection applications in case of NLOS.

6.6 Portal and Cross Reading

An RFID system with STs can readily be used to rectify problems with cross-readings. In this experiment, we demonstrate the feasibility of a solution with STs where the ST detects the proximity of the tag only inside the portal area. A person was wearing a tag (passive

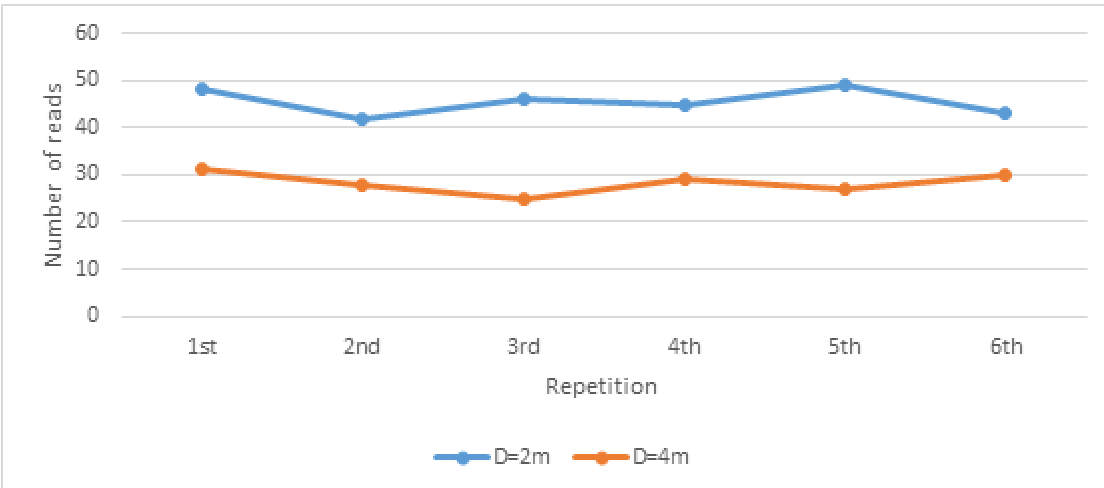


Figure 6.17: LOS experiment for ST-based RFID system: the number of reads by the ST in 15 seconds repeated 6 times.

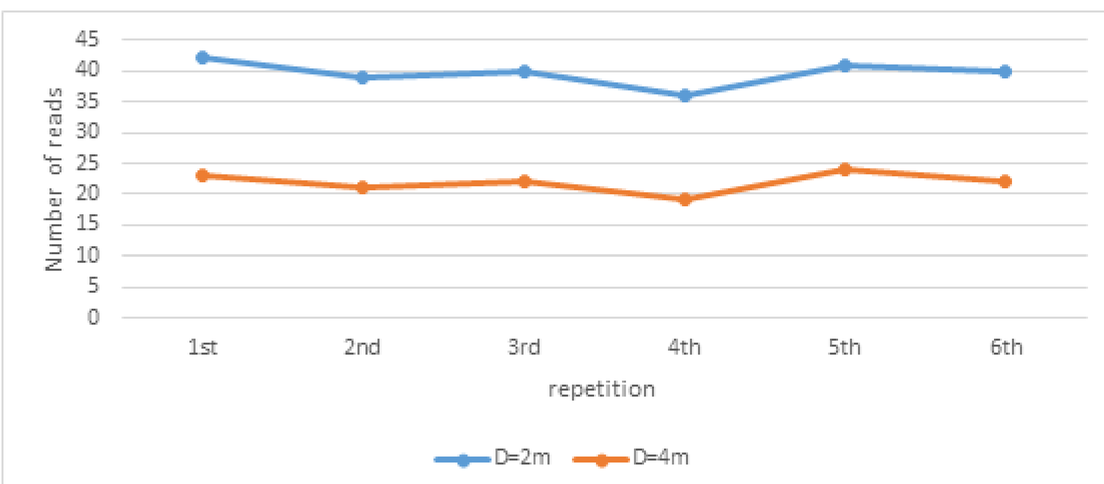


Figure 6.18: NLOS experiment for ST-based RFID system: the number of reads by the ST in 15 seconds repeated 6 times.

UHF tags with chip "MF1S70" from Philips) on the wrist and was passing through an improvised portal made on one reader antenna on the left and the ST on the right. The distance between the ST and the reader was 2 m, the height of the reader antenna was 1.2 m and the height of the ST from the ground was 1.25 m. The tag was detected 100% of the time by the ST and the reader when the experiment was repeated 10 times. When the person with the tag went around the portal (behind the ST) it was not detected at all (0/10 times). A real portal would have, for example, two reader antennas (one on each side) and minimum four STs (at least two on each side). The detection of the tags by the STs will not only be used for determining if the tags pass through the portal but also for estimating the direction of their movement. Since only one prototype of ST was available, doing this experiment and providing measurements and numbers was not possible. However, based on the observations on the portal with one ST, we can expect reasonable results.

6.7 Summary of the Experimental Results

A number of experiments have been performed to evaluate the performance of the STs for proximity detection and IoT applications accordingly. An important metric used in the performance evaluation was the detection rate or read rate of the ST. It represents the number of times the ST detected a tag in a predefined time interval and use it for weighting in WCL method. We tested the detection rate of STs in (a) stationary and (b) mobile settings.

We had several groups of experiments. In the first one we studied proximity detection performance in object-to-object and object-to-human in both stationary and mobile settings. Based on this experiment and the results shown in Table 6.1, we can conclude that the proximity detection rate depends on both the distance between the tag-ST and distance between the tag-reader. Presence of human body has a significant effect on the proximity detection rate and decrease the rate four times on average. The angle between the tag's and ST's antenna can also affect the detection rate. According to the experiment that explained in Section 6.2.3, the ST can detect the tag when the angle between their antenna is between 0 and 60 degree. However, for the angles greater than 45 degree the number of reads are small and not reliable.

In the second experiment we used the capability of the ST in proximity detection, and used this potential for indoor localization. Weighted centroid localization method is considered for estimating the location. Number of tag reads by ST have been used for weights in the method. The error in localizing stationary objects depends on the density of the landmark tags. In the experimental area covered by UHF passive tags (a tag on each 50cm in X coordinate and each 1m in Y coordinate), the mean error for stationary object is 19 cm in X coordinate. The mean error will increase to 24 cm in mobile ST with the speed of 3.68 cm/s, because of changing the detection rate while the ST moves between each report. According to Figure 6.3 we can also conclude that the mean square error depends on the speed of the mobile ST. In indirect localization, ST could report non-landmark tags in the vicinity between 40 and 66%. This is enough for detecting the non-landmark tags every time and for estimating its location. The error of the indirect localization based on the ST is less that its detection range for passive tags.

In the next set of experiment, we used the ST for activity tracking. As long as the human body is not between the ST and reader antenna when it is attached to the body, we can track the activities 100%. The reliability of the ST-based tracking system increases if we attach more than one UHF tag to the object. However, even with one tag on the object we were able to track the movement even though the number of times the tag was detected by the ST dropped three times on average as shown in the Figure 6.10. In the next part of the experiment, ST used to detect and locate movement of objects and people in landmarked area. The results show that the localization accuracy will be less when ST is reporting person tag ID compare to just locating the mobile ST, because ST can report six tags only in its vicinity in each report. However, tracking objects and people in landmarked area can be done in ST-based RFID system as shown in Figure 6.14.

At last, the capability of the ST in cross reading detection has been investigated. The tag was detected 100% of the time by the ST and the reader when it passes through the portal. The number of detection by ST dropped to 0 if the tag went around the portal. Based on this, it can be concluded that ST-based RFID system is a very reliable system for portal applications.

Chapter 7

Conclusion

7.1 Concluding remarks

The IoT will be a network of things where the nodes (things) are intelligent and are able to interact among themselves. In this thesis, we described a UHF RFID system augmented with STs, which are able to address several issues of the IoT. They include unique identification, proximity detection, and localization of the things. We investigated how the STs perform in applications of proximity detection and localization and showed that they have a strong potential for an important role in the IoT. They can be used for detecting proximity of objects and people, tracking moving objects, and detecting if objects are moved from one place to another. The ability of ST in preventing cross-reading can be helpful in enumeration applications in future IoT.

The thesis compared this approach to two other similar implementations using passive systems. The ST-based RFID system offers good performance and low-cost due to the ability to be added to any regular RFID system and using inexpensive elements on the board. The ST suffers from limitations in sensitivity and problems in working near human body. However, the ST-based system does overcome the limitations of the similar implementations, namely it deals with NLOS reading, and allows for localizing the object in a real environment. Quantitatively, the ST-based RFID system achieved an accuracy of 20cm in an area covered by landmark tags(2Ltag/m on each coordination). However, this number can be variable depending on the density of landmark tags. In 100% of times, we can localize items indirectly in the read range of the ST. Different scenarios were implemented to showcase the usability of ST in localization, proximity detection and activity tracking.

7.2 Future Work

The results presented in this thesis are based on the first prototype of the ST. The speed of the system and the ST's orientation sensitivity, size, cost and power consumption need to be improved. The optimization of the power consumption is one of our future efforts. Namely, working on migrating from an FPGA design to a low-power/low-cost MCU that can increase the lifetime of the ST up to one year. The presented system, however, shows that it has potential for various IoT applications.

The current ST supports Miller 4 modulation from the reader and ASK modulation from the tag. One possible extension is to implement all available modes supported by the EPC Gen 2 standard.

One of the big advantages of ST in IoT applications, is data filtering. The protocol and firmware of the ST can be changed to receive special commands from the reader and act as a middleware in RFID system to filter the data.

The current implementation of the ST is not optimized to work near human body. One extension is to optimize the ST front-end circuit to work better near human body.

Another suggestion for future works is expanding the capabilities of the ST by adding energy harvesting techniques to increase the battery life time. Also changing the protocol to let STs communicate to each other can open many windows for new applications of IoT using ST.

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