Radio Frequency Localisation/Tracking of RFID Tags in a Raspberry-Pi Sensor Network

Aleksandar Krastev

Master of Science
Computer Science
School of Informatics
University of Edinburgh
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Abstract

To Do

Acknowledgements

I thank my supervisor Dr Michael Rovatsos and Mr Michael Anslow for their support and patience.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(*Aleksandar Krastev*)

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Chapter 1

Introduction

Copied from IRP

Radio Frequency Identification (RFID) is an identification technology that also enables tracking of people and objects. RFID functions by remotely obtaining data stored on RFID tags. This information is mainly used for identification purposes. Systems relying on such data can only provide course-grained location information [Bouet and dos Santos, 2008]. Their RFID readers are positioned at strategic control points in order to recognise tags that enter their read range. However, if an object's identity is combined with its location, then the benefits of RFID could be greater. For example, patient care and hospital operations could be improved using remote identification and tracking of patients [Cangialosi et al., 2007].

RFID localisation principles are similar to the ones used for indoor wireless networks [Bouet and dos Santos, 2008]. There are certain differences between both technologies, which results in tracking methods that are altered to reflect the characteristics of RFID. This project uses some of these indoor localisation schemes to detect and track a tag using three reader nodes in a controlled indoor environment.

RFID systems mainly consist of tags and readers. While tags are simple devices, readers are more complex and usually require a connection to a host computer or network [Landt, 2005]. The high costs of tags and readers are a major factor that constrains the penetration of this technology [Want, 2006]. Nowadays, these devices are becoming affordable to users . In addition, the recent emergence of cheap and compact single-board computers, such as the Raspberry Pi[1], creates an exiting opportunity to build a cost-effective RFID sensor network capable of localising tags. This can be realised by connecting readers to single-board computers through USB or wired using a breadboard[2] and general purpose input/output (GPIO) pins on a chip.

On the one hand, the RFID technology has unprecedented advantages and it has gained the attention of big industries that have identified its potential. On the other hand, the high costs of RFID tracking systems and components prevent most people from using and developing the technology. The hardware combination of affordable readers, tags, and single-board computers has the potential to benefit a vast range of businesses but also do-it-yourself hobbyists and enthusiasts. This might result into improved automated handling and tracking of goods in a warehouse, for instance. It

[1] About the Raspberry Pi - `http://www.raspberrypi.org/about`

[2] Breadboard is a solderless (plug-in) construction base used for experimenting with circuit design.

can also result in a fast-paced, community-based, and open-source development of the RFID technology applied in a wide range of scenarios. This project is interesting and exciting because it will try to apply RFID localisation algorithms on affordable hardware in order to create a tracking system. This will show that there can be cost-effective alternatives to commercial solutions, thus making the technology more accessible to a wider audience.

1.1 Hypothesis

Copied from IRP.

The hypothesis of this project is that existing algorithms for localisation and tracking of active tags can be applied on a cost-effective Raspberry-Pi-based sensor network to achieve a similar performance. More specifically, the purpose of the project is to construct and programme three reader nodes, each consisting of a reader connected to a single-board computer, that cooperate in an indoor environment to estimate the position of a stationary or moving active tag based on the Received Signal Strength Indicator (RSSI) using a localisation method called trilateration.

1.2 Contributions

1.3 Thesis Outline

1.4 Summary

Chapter 2

Background

This chapter presents background information of the technologies and hardware used in this project. First, an introduction of RFID is provided in Section 2.1. This includes a description of the technology, typical components of such systems, and potential applications in the context of this work. Then, Section 2.2 discusses the Received Signal Strength Indicator (RSSI) as the metric for measuring distance between readers and tags. Next, the hardware components of the project are presented in Section 2.3. These are RFID readers, an active tag, and single-board computers (Raspberry Pis). Section 2.4 includes a discussion of location sensing techniques and evaluation criteria used throughout this project. This chapter is concluded by a survey of previous work using active RFID components to localise objects in indoor environments.

2.1 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a wireless technology that communicates electronically stored data between radio devices. This information is used to remotely identify objects marked with tags [Hunt et al., 2007, p. 5]. RFID uses electromagnetic waves to carry information. Such systems differ from each other by their radio frequency of operation, physical coupling method, and transmission range [Finkenzeller, 2010, p. 21]. Radio frequencies used in RFID range from 100kHz to 10GHz [Landt, 2005]. The physical coupling methods in RFID classify such systems into three main categories. Close-coupling systems have a small interrogation range of up to 1cm. Remote coupled systems are capable of sensing information of up to 1m. All systems that can wirelessly read data from a marked object positioned over 1m away are called long-range systems [Finkenzeller, 2010, p. 22]. An RFID system has three compulsory hardware components, tags (also known as transpoders), readers (also called interrogators), and controllers.

2.1.1 RFID tags

A tag is a data-carrying device that transmits identification information in response to a received signal from a reader. RFID tags usually consist of an antenna attached to a microchip [Want, 2006, p. 2]. The hardware can be encapsulated in different types of enclosures. Tags come in different shapes and sizes depending on their operational

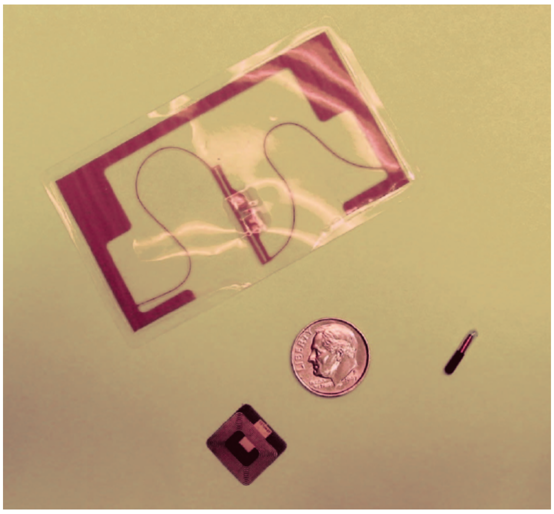


Figure 2.1: Three different variants of RFID tags. Figure from [Want, 2006].

environment (Figure 2.1). RFID tags also have memory where the identification and sometimes additional information is stored. Additional data might include a delivery date of a parcel, for example. The information stored on a tag is usually only for reading. However, there are implementations of the RFID technology that benefit from writing data to a tag. For instance, a pallet might have a tag attached to it that can store the content of the pallet as it changes over time [Hunt et al., 2007, p. 8].

2.1.1.1 Passive and active tags

Tags can be classified into two main categories, passive and active . Passive tags do not require a power source. They communicate with readers by reflecting part of received radio waves, a term referred to as backscatter modulation [Bolic et al., 2010]. They have a number of advantages, which include their small size, very long operational life, and low price. Nevertheless, passive tags need to be in the readers' range in order to operate. This is because passive tags obtain the power they need to supply their circuitry from an electromagnetic signal received from an RFID reader. A charge builds up into a capacitor that can power the passive tag and transmit the identification information it is storing [Weinstein, 2005].

In contrast, active tags require a power source in the form of a battery or are directly connected to the electrical grid [Want, 2006]. Although, their lifetime might be limited by the available energy, active tags can be read from greater distances compared to passive tags. This is because they have their own power source which enables them to emit strong signals to the readers [Weinstein, 2005]. Compared to passive tags, active ones are larger in size and have a higher price.

2.1.2 RFID readers

A reader is a radio device that is capable of transmitting interrogation signals and capturing information send back by tags. The reader's transmission frequency specifies the operational frequency of the RFID system, which also defines their practical reading range [Finkenzeller, 2010]. These devices usually consist of a radio frequency (RF) module, that is capable of sending and receiving signals, an antenna, and a control unit in the form of a microprocessor. RFID readers have the following main functions:

- read/write data from/to an RFID tag,
- power a passive tag,
- relay the obtained information to a host computer [Hunt et al., 2007, p. 9].

Readers are responsible for bringing additional functionality to an RFID system. This includes support for simultaneous sensing of multiple tags, authentication of tags to prevent unauthorised access to a system, and data encryption of the stored data to ensure integrity [Hunt et al., 2007, p. 10]. There are a wide range of RFID readers that differ in their operational radio frequency, range, and coupling method. These properties are formed by factors such as the specifications of the system, its budget, and security requirements [Finkenzeller, 2010, p. 25].

2.1.3 RFID controllers

The third component of an RFID system is the controller or server. It is a computer that is responsible for connecting and communicating with multiple readers, aggregating any incoming data, and processing it. Readers can be connected to the server using a network or serial connection. Identification information is usually stored in a database and is used by an application software [Hunt et al., 2007, p. 11]. Figure 2.2 shows the components of a typical RFID system.

Figure 2.2: Components and applications of RFID. Figure from [Rida et al., 2010, p. 20].

2.1.4 RFID applications

RFID hardware is becoming more inexpensive, which creates a wide range of possible scenarios where this technology can be applied [Nath et al., 2006]. The most widespread applications are in tracking of objects or people, in supply chain and asset management, and in health services [Weinstein, 2005].

Passive RFID systems can be used as an alternative and improvement of the current standard for identification of products, the barcodes. Reading a barcode attached to an object requires a direct line of sight between a reader and a tag. In addition, barcodes can get obscured by other objects or substances, which hinders the identification process. RFID solves these disadvantages. A line of sight is not required when reading data from tags attached to objects. RFID tags also support a larger set of unique IDs compared to bar codes, can be reprogrammed, and can store additional data depending on the application requirements [Weinstein, 2005].

In the context of this project, which is concerned with location sensing, RFID has applications in tracking important objects or personnel and trying to pinpoint their position. For example, active RFID systems can be used in hospitals to monitor the location and life cycle of patients in an indoor environment [Cangialosi et al., 2007]. Expensive hospital equipment could be tracked so that it would be at the right place and time. Another possible scenario is to track school kinds while on school grounds in order to find lost children and monitor their attendance [Swartz, 2004].

2.2 Received Signal Strength Indicator (RSSI)

Some RFID readers provide an indication of the strength of radio signals received from tags. This metric is called Received Signal Strength Indicator (RSSI). Its value is often output along with the identity information stored in a tag. It is estimated at the reader side before amplifying the received input. RSSI is an uniteless measurement of the power of the received signal represented as a positive value with certain resolution range. A resolution of three bits gives a precision of eight possible values for RSSI. This means that there are eight different steps of estimating how far a tag is. A resolution of eight bits, supported by the project hardware, lets readers output values between 0 and 255 giving a better approximation of the distance between a reader and a tag.

2.2.1 RSSI and RSS

RSSI is not to be confused with the Received Signal Strength (RSS), on which RSSI is based. RSS is usually measured in dBm[1]. It represents the attenuation of a received signal and is a function of the distance between a receiver and transmitter [Bouet and dos Santos, 2008]. In WiFi, the 802.11 standard does not define the relationship between RSSI values and reported signal power levels. It is up to the manufacturers to provide a conversion function or table that specifies range and accuracy of

[1] dBm - Power ratio in decibels of power referenced to one milliwatt (mW) - `http://en.wikipedia.org/wiki/DBm`

the RSS values and how these translate into a RSSI range between zero and a maximum value [Lui et al., 2011]. The above applies to RFID, which is also a radio technology.

2.2.2 RSSI and distance

A third relationship is the one between RSSI and distance. In other words, it is the problem of using RSSI reader measurements to estimate the distance separating a receiver and transmitter. More importantly, one might ask whether RSSI is a reliable parameter for localisation algorithms in wireless networks. This is not the main question that this work is concerned with. However, the reliability of this measure is of prime importance because here position estimation relies solely on this parameter.

On the one hand, there are studies that test the reliability of both RSS and RSSI for location sensing [Elnahrawy et al., 2004, Parameswaran et al., 2009]. These concluded that the limitations of determining inter nodal distances are fundamental. On the other hand, signal strength is readily available in devices today, which creates attractive opportunities for estimating position without any additional hardware. Indeed, there are a number of WiFi-based systems that rely on received signal strength including the Horus WLAN location system [Youssef and Agrawala, 2005], the EZ localisation system [Chintalapudi et al., 2010], an indoor location system using trilateration [Cook et al., 2005].

2.2.3 How RSSI fits in this project

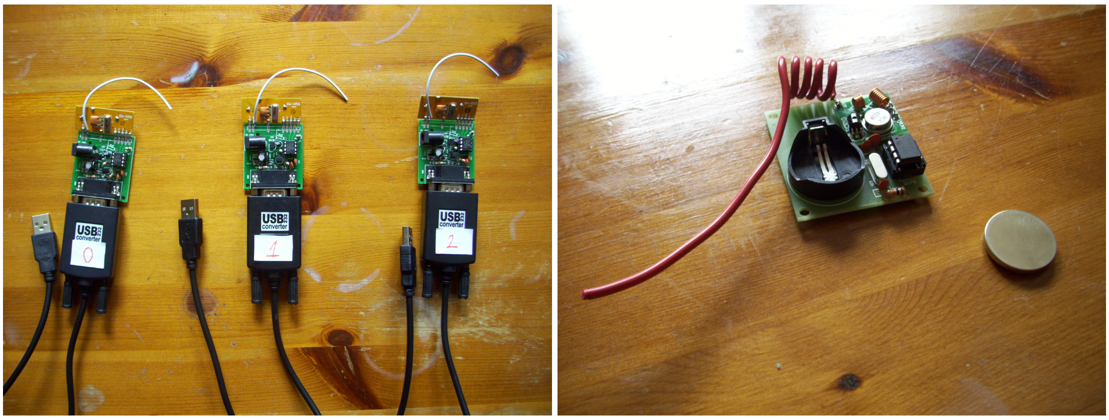
Although RSSI is not considered a reliable measure for distance due to the physical properties of radio waves and due to cluttered and dynamic indoor environments, the aforementioned systems show that researchers and engineers try to get the best of what is already provided. In the same manner, this work uses RSSI reader measurements as a basis for location sensing. This is done using a translation table that converts RSSI into a distance metric. The methods used and the challenges faced are discussed in **REF**.

2.3 Project Hardware

This project combines three types of hardware. The first is active RFID devices, the second - single-board computers, and the last is a commodity network infrastructure. The main hardware components can be seen on Figures 2.3 and 2.6. The following subsections present these devices and their specifications. Details on how the components are combined in forming the resulting system are given **REF**.

2.3.1 RF9315R-u Active RFID 8 Meters Receiver with RSSI Module

The project uses three active RFID readers containing RSSI modules. Figure 2.3a shows the three readers, where each is connected to a serial to USB converter that offers a convenient interface to any computer with USB ports. For a discussion of the problems encountered while using the converters refer to **REF**.



(a) Three active RFID readers (b) One active RFID tag

Figure 2.3: RFID hardware used in this project.

The readers are superheterodyne receivers meaning they convert received signals to an intermediate frequency that is more convenient to process and gives a more stable design. The readers operate at 315 MHz, which lays in the lower band of Ultra High Frequency (UHF). Such waves propagate mainly by line-of-sight. They are blocked by large objects such as buildings but can penetrate through a few building walls, which is enough for indoor location sensing. UHF are also sensitive to antenna orientations [Hunt et al., 2007, p. 15].

The readers get their power supply from a serial or USB connection (when serial to USB converter is used). The readers have a DC 9V socket that can be used to power the devices in case the above connections are not able to supply sufficient power. The receiver devices have a built-in watchdog timer of 2.3 seconds. The watchdog timer is used to detect hardware malfunction. The readers reset the time before it elapses to confirm that they are operating correctly. These receivers can read up to 80 tags simultaneously. There is not any anti-collision protocol. The readers rely on the tags to transmit their identification data every 2.5 to 3.0 seconds.

The RFID readers employ a simple communication protocol. The serial port settings for these devices can be seen in Table 2.1. Data is send in a raw character format without data encryption. The ID of a tag, consisting of four characters, is concatenated with a RSSI measurement, which could range from 0 to 255. For a discussion on the actual RSSI ranges observed during experiments refer to **REF**. Each new reading is separated by a space character. A sample input from the RFID readers is illustrated on Figure 2.4.

Parameter	**Value**
Baud rate	9600 bits per second
Data bits	8 bits
Stop bits	1 bit
Parity	None
Flow control	None

Table 2.1: Serial port parameter settings to communicate with the readers.

Figure 2.4: RFID reader input on a communication port. The first four characters are the ID of a tag. The number concatenated to the ID is the RSSI value. Individual readings are separated by a space character.

The integrated RSSI module measures the received radio frequency signal over a range of 60 dBm. The manufacturer specifies that RSSI values vary between units[2]. Figure 2.5 shows how the radio frequency signal level on the x axis changes against the RSSI voltage on the y axis. In can be observed that the signal levels can be effectively measured between -55 and -115 dBm giving a range of 60 dBm. The reader specifications described above are summarised in Table 2.2. These reader devices are a good fit for this project because of their low price, RSSI modules with good resolution, active RFID type, and USB connectivity.

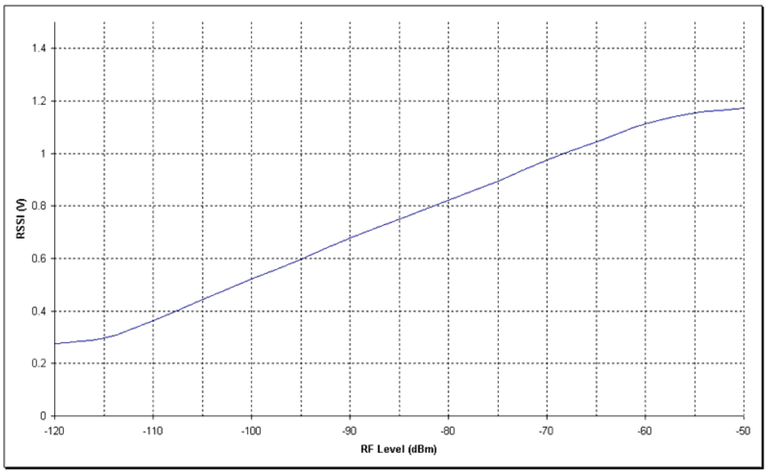


Figure 2.5: A plot of radio frequency signal levels against RSSI voltage. Figure from product website[2].

2.3.2 RF8315T Active RFID 8 Meters Transmitting Module

The active tag is a radio transmitting device that sends out its unique four character identification every 2.5 $\pm$ 0.5 seconds. Figure 2.3b shows the active RFID tag used

[2] Ananiah Electronics active RFID reader - `http://www.ananiahelectronics.com/RF9315R-u.htm`.

Specification	Value
Dimensions	4cm x 6cm x 1.8cm
Operating Temperature	0 - 50° C
Operating Frequency	315 MHz
Incoming signal range	60 dBm
Power source	Serial / USB port, DC 9V socket
Communication	R-232 serial port
Watchdog timer	2.3 seconds
Simultaneous reads	80 tags
Reader control	No control protocol
Data representation	Raw character data, No data encryption
Data output	ID: 4 characters + RSSI: 0-255
Price	US $49.95

Table 2.2: Specifications of RF9315R-u active RFID reader. Table from product website[2].

in this work. Its transmission time is around 11ms giving a small probability of tags' signals colliding. The tag can use CR2025 and CR2032 batteries as a power supply. It can operate between 5,000 and 7,000 hours with a single battery. The tag consumes most of its power (4mA) while transmitting. During the rest of the time, the tag stays into hibernation mode using only 18uA.

The effective transmission range of the tag is estimated at 8 meters by the manufacturer. For range measurements conducted during this project refer to **REF**. The tag arrived without an antenna. According to the specifications, to achieve its effective range, the antenna should have a 8mm coil diameter and 2cm coil length. The construction of the antenna is discussed in **REF**. The tag specifications described above are summarised in Table 2.3. This RFID tag was chosen for this project because of its low price, transmission range, portable size, low power consumption, and matching operating frequency to the readers.

Specification	Value
Dimensions	4cm x 5cm x 1.8cm
Operating Temperature	0 - 50° C
Operating Frequency	315 MHz
Power source	CR2025 / CR2032 battery
Battery life	5,000 / 7,000 hours
Power consumption	4mA when transmitting, 19uA when idle
RF output power	$<$ 2mW
Effective range	8 meters with 8mm coil diameter, 2cm long antenna
Data output	ID: 4 characters
Price	US $19.95

Table 2.3: Specifications of RF8315T active RFID tag. Table from product website[3].

2.3.3 The Raspberry Pi

A single-board computer is a computer that is built on a single circuit board. It features most of the components of a personal computer. It has a processor, memory, storage, different microprocessors, and input/output interfaces. The Raspberry Pi is a particular implementation of a single-board computer. This project uses three such devices in order to construct a location sensing system. Figure 2.6a shows these computers.

The Raspberry Pi has compact dimensions and is low on weight. It consumes little power but has enough processing power, memory, and storage to run a standard operating system, such as the Raspbian Linux. The Raspberry Pi has two USB 2.0 ports as well as an Ethernet network port. In addition, the Pi has some characteristics of a development board employing a General Purpose Input/Output (GPIO) interface, which is could be used for connecting low-level peripherals such as RFID readers. The characteristics of the Raspberry Pi make it a great candidate for this project. Its specifications are summarised in Table 2.4.

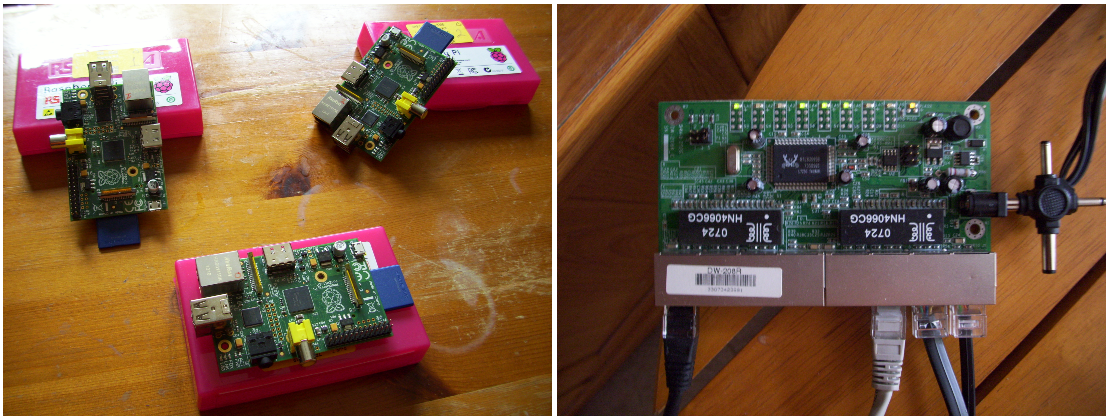
Specification	**Value**
Dimensions	86mm x 54mm
Weight	45g
Power source	5V MircroUSB or GPIO
Power rating	700mA (3.5W)
System on a chip	Broadcom BCM2835
CPU	700MHz ARM1176JZF-S
GPU	Broadcom VideoCore IV 250MHz
Memory	512MB
Storage:	SD card slot
USB 2.0 ports	2
Networking	10/100 Ethernet
Low-level peripherals	8 x GPIO, UART, I^2C bus, SPI bus
Operating system	Raspbian Linux
Price	US $35

Table 2.4: Specifications of the Raspberry Pi Model B revision 2 single-board computer. Table from product website[4].

2.4 Location sensing

Estimating the position of an RFID transmitter using three receivers is the main goal of this project. This section describes a localisation technique that is suitable for the available hardware. It also defines criteria for evaluating estimated positions.

[3]Ananiah Electronics active RFID tag - `http://www.ananiahelectronics.com/RF8315T.htm`.
[4]The Raspberry Pi website - `http://www.raspberrypi.org/faqs`.



(a) Three Raspberry Pis (b) LAN switch

Figure 2.6: Computer and network hardware used in this project.

2.4.1 Trilateration

Trilateration is a localisation technique that uses the geometric properties of triangles in order to compute locations [Hightower and Borriello, 2001a]. This technique has practical applications in surveying and global positioning systems. Trilateration requires the known locations of two or more reference nodes as well as the distance measurements between a reference node and the unknown object [Zhang et al., 2009, p. 280]. In this project, the distance from a reader to a tag is the radius of a circle that could be drawn around the reader. The intersection of circles of three readers can be used to determine the approximate location of a tag relative to the readers. In order to compute the position of an unknown object in two dimensions, trilateration requires three reference points that are non-collinear [Zhang et al., 2009]. In a three dimensions case, four non-coplanar nodes and their distance measurements are needed [Hightower and Borriello, 2001a]. Figure 2.7 shows a graphical representation of the concept of trilateration.

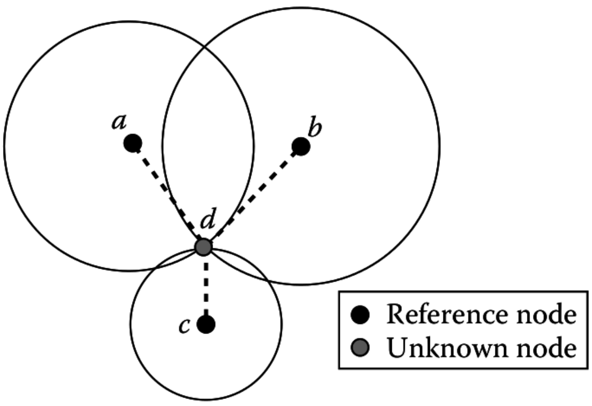


Figure 2.7: The trilateration technique for positioning an unknown node based on distance measurements from three reference nodes. Figure from [Zhang et al., 2009, p. 281].

2.4.2 Evaluating an estimated position

An important requirement for every location system is to estimate positions consistently and accurately. Hightower [Hightower and Borriello, 2001a] proposed criteria for the classification of such systems based on properties including accuracy, precision, and distribution of erroneous positions to the true one. Such metrics can be used when evaluating a location system's performance in terms of how often it locates an object within some distance of its true location. For instance, if a GPS receiver can locate its position within 5 meters for 90 percent of the time, then its accuracy is 5 meters and has a precision of 90 percent for that accuracy [Hightower and Borriello, 2001b]. There is a trade-off between accuracy and precision. To achieve a higher precision, one might have to sacrifice accuracy. As a result, in order to arrive at a concise quantitative summary of these attributes, Hightower proposed to assess the error distribution accumulated during a system's operation [Hightower and Borriello, 2001b]. In addition, this should be combined with other parameters such as the number of nodes in the system, the density of the infrastructure, and the size of the indoor space. Here we to use these metrics in order to evaluate the localisation performance of the resulting system.

2.5 Previous work

The RFID technology is of substantial interest to researchers. Location sensing using active RFID devices is a specific subcategory of this field. Nevertheless, there have been a number of important research efforts to construct localisation systems using the available RFID hardware at that time. This section presents some of the previous work that directly relates to this project.

2.5.1 SpotON

SpotON is a fine-grained tagging technology for 3D location sensing using radio signal strength analysis [Hightower et al., 2000]. The author's motivation was to develop a low cost system compared to commercial solutions available at their time. SpotON's operation involves a number of readers collecting signal strength information from active tags to determine their positions in the 3D space. It was the author's believe that the accuracy and efficiency of location sensing could be enhanced by sensor fusion, i.e. adding more sensors (accelerometers) and building proximity maps [Hightower et al., 2000].

2.5.1.1 Operation

The SpotON algorithm consists of two main parts. First, RSS measurements are converted into a distance estimation. This is done using a translation function relying on numerical variables that were identified based on observation. This function is hardware-specific and cannot be applied in this project. Second, distance measurements are used as an input to a localisation algorithm that tries to minimise RSS errors

[Hightower et al., 2000]. It is based on the lateration geometrical process to estimate a position for an active RFID tag.

2.5.1.2 Limitations

At the time or their research, Hightower and his colleagues were using RFID hardware with 2-bit accuracy when measuring received signal strength [Hightower et al., 2000]. They identified that this accuracy is not enough to achieve the precision required for localisation in small indoor environments. The authors mentioned that 8-bit accuracy (supported by this project's hardware) could be used in the future for improved performance [Hightower et al., 2000]. Another limitation was the frequency of collecting measurements. This would take between 10 and 20 seconds, which is generally too slow for monitoring real-time position changes of objects. These drawbacks were solved by creating custom RFID hardware.

2.5.1.3 Results

When localising a tagged object, the SpotON system achieved accuracy of 3 meters using off-the-self hardware [Hightower et al., 2000]. Relying on their custom RFID devices, SpotON reported under 1 meter location sensing accuracy.

2.5.2 LANDMARC

LANDMARC is a 2D location sensing system that uses RFID for locating objects inside buildings. The major advantage is that it improves the overall accuracy of locating objects by using reference tags [Ni et al., 2004]. The authors believed that the choice of technology and techniques is of crucial importance for the granularity and accuracy of the location information. They identified that the range of an RFID system is determined by the power available at the tags, indoor topology, and environmental conditions. Ni and his colleagues found out that instead of using a lot of readers, they can arrange a number of tags in a 2D rectangular grid to use as reference tags [Ni et al., 2004]. The advantage is that tags are cheaper than readers. Also reference tags are subject to the same environmental factors as the tags being tracked. The authors argue that the placement of readers and reference tags is very important for the accuracy of the system [Ni et al., 2004].

2.5.2.1 Operation

The core idea of LANDMARC is to select the k nearest reference tags that are closest to the unknown tag using differences in RSS measurements. Having identified the k nearest reference tags, their known positions are used to localise the unknown tag. Distances between tags are computed using Euclidean distance. The system also applies a weighing factor when computing coordinates, where small distances receive a bigger weight.

2.5.2.2 Limitations

The hardware problems of the current RFID technology were identified [Ni et al., 2004]. RFID hardware used in LANDMARC did not supply signal strength directly, which resulted in unnecessary processing and sacrificed accuracy. LANDMARC took a substantial time to estimate locations. Two factors were contributing to these problems. One being the scanning time of the readers in order to collect signal strengths. The second, the time interval of a tag emitting its identification information, which could not be controlled. Ni and his colleagues also measured different power levels from two tags placed at identical positions. This resulted in unstable system behaviour.

2.5.2.3 Results

The authors experimented with different number and placement of readers, reference and tracking tags. The best setup was consisting of 4 readers and 1 reference tag per square meter resulting in an average distance error of 1 meter [Ni et al., 2004].

2.5.2.4 Extension systems

VIRE extends the methods used in LANDMARC by defining virtual reference tags and a proximity map that every reader records [Zhao et al., 2007]. This proximity map consists of a 2D grid of reference tags where the centre of a cell is a tag. The difference in the RSS measurements between reference and unknown tag helps label cells in the proximity map so that it can be constructed. The union of individual proximity maps gives a global proximity map for the unknown tag. Experimental results showed an improvement of LANDMARC's precision between 17 and 73 percent for different scenarios and indoor environments [Zhao et al., 2007].

LANDMARC is a location sensing system that reports a two dimensional tag positions. The extended 3-D LANDMARC algorithm is a system that could localise tags in three dimensions [Khan and Antiwal, 2009]. A major difference is the use of passive tags instead of active ones. This system solves some of the original limitations of LANDMARC by using hardware providing received signal strength directly. The authors rely on similar methodology but extend computations to three dimensions. The accuracy of the system was estimated at around 0.5 meters when employing 3 readers, 2 tracking tags, and 11 reference tags in a 11 cubic meter space [Khan and Antiwal, 2009].

2.6 Summary

This chapter presented background information of the technologies and hardware used in this project. First, an introduction of RFID is provided in Section 2.1. Then, Section 2.2 discusses the Received Signal Strength Indicator (RSSI). Next, the hardware components of the project are described in Section 2.3. Section 2.4 includes a discussion of location sensing techniques and evaluation criteria. This chapter is concluded by a survey of previous work relating to this project.

Chapter 3

Methodology

This project explores the possibility of developing an RFID location sensing system using cost-effective hardware. This chapter details the software engineering tools and mathematical techniques that were employed to achieve this goal.

3.1 Project management

A number of considerations were taken into account when deciding how to manage this project. First, the system operates using a server-client model. This means that different software components are executing on multiple processing nodes. As a result, changes in one node need to be propagated in the whole system ensuring the consistency of the software. Second, the software implementation is making use of different programming languages, multiple programming libraries, and a database management system. In order to insure an iterative development process, where software components are constructed, reused, debugged, and packaged together, it was decided to use the GIT version control system. This system keeps a distributed repository of all software and database files so that each node stores a copy of not only the whole software system, but also a complete history of changes. In addition, the use of a version control system stimulates the developer to summarise a number of important changes into versions of the software. In this way, it becomes easy to track and examine the project's progress.

3.2 Software Engineering Practices

A number of software engineering practices were of great help when developing the RFID location sensing system. This section presents them and explains the problems that they solve.

3.2.1 Project decomposition

It would have been a serious challenge to approach the project's task directly. The system consists of pieces of hardware that had to be orchestrated to solve a common problem. Therefore, it was very important to identify the system's components from early on. Hierarchical relationships between these parts were also defined. These steps ensured that the project could be divided into stages in order to systematically solve the main task. Regular deliveries of working components provided a more manageable way of constructing the final solution. For example, the work plan, devised before the start of the project, consisted of the following key activities:

1. Prepare the single-board computers
2. Construct functional RFID reader nodes
3. Receive information from the active RFID tag
4. Establish a network communication between nodes
5. Develop the localisation algorithm

Iterative construction of the system aided the development process. Problems were appearing gradually which helped solving them one at a time.

3.2.2 Object-oriented design

This location sensing system is a combination of different software technologies. For instance, the system required an interface between a single-board computer and an RFID receiver. It also required means of communication between processing nodes. Logically, these and other requirements could be grouped into sets of functions, which is a motivation for employing an object-oriented design. This software methodology was used from the beginning of the project. Similar functionality is organised in a class. A class is responsible for all procedures concerning a particular part of the system. As a result, software is split into categories of functions, which makes it easy to address the class in charge of certain functionality.

Another benefit of the object-oriented design is modularity. For example, once input data is collected from all nodes it could be processed by a localisation algorithm in order to estimate the tag's position. Trilateration was chosen as the technique for computing locations. Object-oriented software development provides an easy way to experiment with different algorithms by exchanging one class with another.

3.2.3 Scalability

3.2.4 API and Manual

iteration, design, systematic approach, decisions, resolving problems,

3.3 Translating RSSI to distance

3.4 Trilateration

3.5 IRP

This project can be decomposed into a number of parts that include several small steps. Each part delivers an important piece of the system. This way the project is more manageable and each deliverable presents a working and tested component of the system.

3.5.1 Preparing the Raspberry Pis

The first part of this project concentrates on the single-board computers. This phase is mainly concerned with setting up each individual device with an operating system. This involves installing a Linux operating system using the Raspberry Pi Linux kernel[1]. The kernel needs to be cross-compiled on a standard x86 computer to run on the ARM architecture used by the Raspberry Pi. This kernel will be used in combination with a particular Linux distribution. The Debian[2] Linux distribution will be used. This is because it is a popular and well-maintained distribution with thousands of software packages. After installing an operating system on the three Raspberry Pi computers, they will be tested on how well they run with it. This involves checking that the computer's ports are working and that the computers can communicate over a network.

3.5.2 Constructing a reader node

The next part of the project is to construct three RFID reader nodes each consisting of a reader connected to a single-board computer. The Rasberry Pi has a number of general purpose input/output pins as part of its board. It also has two USB ports. Both connectivity methods can be used to connect an RFID reader. There are a number of issues that arise from the readers and single-board computers.

A reader can output its readings using a serial connection or a USB connection. If a reader uses serial output pins then these need to be connected to the Raspberry Pi's GPIO pins via a breadboard that has a simple circuit. This scenario requires more time, resources, and effort but has been proven to work in many cases in the Raspberry Pi's community forum[3].

If the readers communicate through USB then it is a matter of connecting the two pieces of hardware. Nevertheless, there have been a number of reported issues related to the functionality and reliability of the Raspberry Pi's USB ports[4]. Moreover, it is not

[1] GITHUB repository of the Raspberry Pi Linux kernel - `https://github.com/raspberrypi/linux`

[2] DEBIAN is a GNU/Linux operating system - `http://www.debian.org/`

[3] Raspberry Pi Forum - `http://www.raspberrypi.org/phpBB3/index.php`

[4] Raspberry Pi's USB problems - `http://www.raspberrypi.org/phpBB3/viewtopic.php?f=28&t=23544&hilit=usb+redux`

certain if the computers will correctly recognise the readers in software. As a result, those problems might affect the operation of the system that this project will create.

3.5.3 Reading data from a tag

After constructing three reader nodes, they need to be tested and calibrated by reading identity information and RSSI values from an active tag. Most readers' data can be captured with a number of command-line tools on Linux. An important step is to be able to parse this information and disambiguate its meaning. Fortunately, active readers and tags have been tested and reviewed on the Internet providing valuable information about their data representation[5].

There is an important hardware issue to bear in mind when relying on tag data. This project will be using cheap hardware solutions in order to construct an affordable RFID tracking system. An inherent property of such RFID hardware is that RSSI readings of the same tag measured from the same distance may vary. In order to mitigate this issue, the following steps need to be taken. Every reader need to capture RSSI values of an active tag in various distances and orientations. Then, these readings have to be compared with each other to identify substantial differences. This is required because upper layers of the system will extensively rely on these values to estimate the location of a tag. RSSI measurements are also influenced by the power sources of both readers and tags, their orientation, size of the indoor environment (receiving reflected radio beams), any objects that lie between a reader and a tag. All this factors need to be taken into account when processing RSSI data in software. This might include averaging RSSI values over some time frame and dropping values that greatly differ from previous ones.

3.5.4 Communication between reader nodes

After obtaining a reliable stream of identification and RSSI data from the reader nodes, this information needs to be communicated between devices. A *basic* setup will involve using the computers' Ethernet ports to connect them to a switch. A requirement of this part of the project is to establish a simple protocol for the transfer of information between the devices. They will communicate through network sockets and will both listen and send information through these sockets. Information that could be send could be strings containing measurements but also serialised objects if an object-oriented design is employed. The resulting network will be sufficient for the exchange processed reader information. An *advanced* network setup, which removes the need of network cables, uses the second USB port on the Raspberry Pi to plug a wireless dongle. In this case, one of the computers is designated as an access point and the others connect to it. However, this approach requires more resources and maybe a powered USB hub.

[5] OPENBEACON active RFID platform review - `http://blog.amal.net/?p=247`

3.5.5 Implementing a localisation algorithm

If the previous components work as expected, one single-board computer will be receiving a constant stream of data from its neighbouring peers as well as from its own RFID reader. This information will be used to estimate the position of an active tag relative to the readers. A localisation algorithm will be implemented to run on a single Raspberry Pi. This can be accomplished in a number of programming languages but a implementation language is not chosen yet. However, Python, Java, or C are all good candidates. An advanced setup might involve distributed computation of certain parts of an algorithm that do not depend on each other. This can be done to better utilise the processing power of the single-board computers.

A good starting point is to implement the SpotOn [Hightower et al., 2000] algorithm because it uses Received Signal Strength (RSS) measurements and an active tag to laterate its location. RSS values are approximated into a distance using a function defined with empirical data [Bouet and dos Santos, 2008]. Difficulties that might arise during the main software implementation include:

- accurately estimating distance based on RSS,
- reliable localisation using trilateration,
- achieving similar results using an existing algorithm on this hardware.

3.5.6 Improving the system

As mentioned in previous subsections, some parts of the system allow for improvements or advanced features, such as using a wireless communication between reader nodes or distributed computation of location information. The Raspberry Pis provide sufficient computing power with low energy consumption which creates a vast range of opportunities to utilise their processing power. For instance, a practical idea is to set up a web server on one of the computers in order to monitor identification information and positions of the tag over the Internet. This way every reader node can provide different services and alleviate the need for additional hardware components to construct an RFID sensor network. This project could also benefit from a good software engineering design because, if successful, it can be made available as an open-source project on the Internet, which might benefit RFID and Raspberry Pi communities. If time permits, the software implementation will be made as flexible and modular as possible in order to enable its application in different scenarios and hardware.

3.6 Summary

Chapter 4

Design and Implementation

4.1 Summary

Chapter 5

Evaluation

5.1 Summary

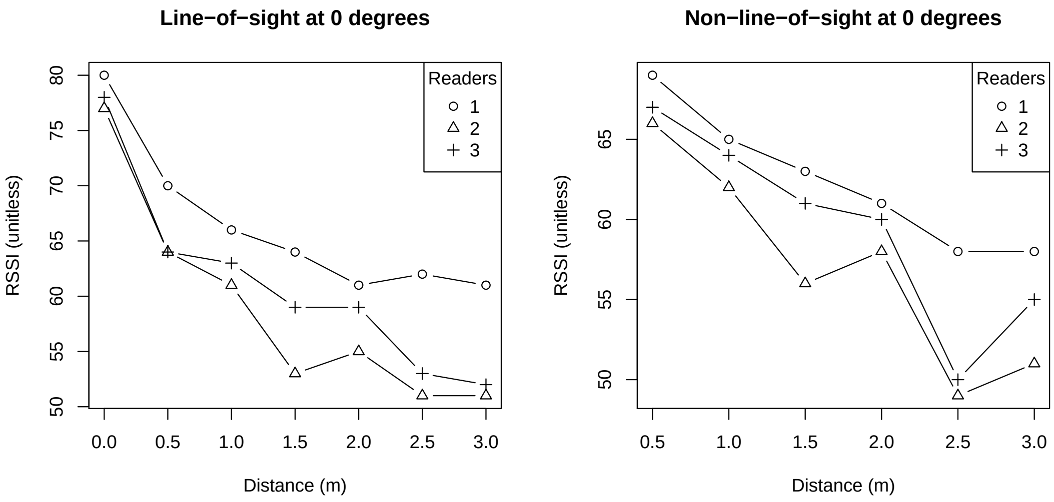


Figure 5.1: Two plots of RSSI measurements at increasing distances with the readers at 0 degrees (antennas facing the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

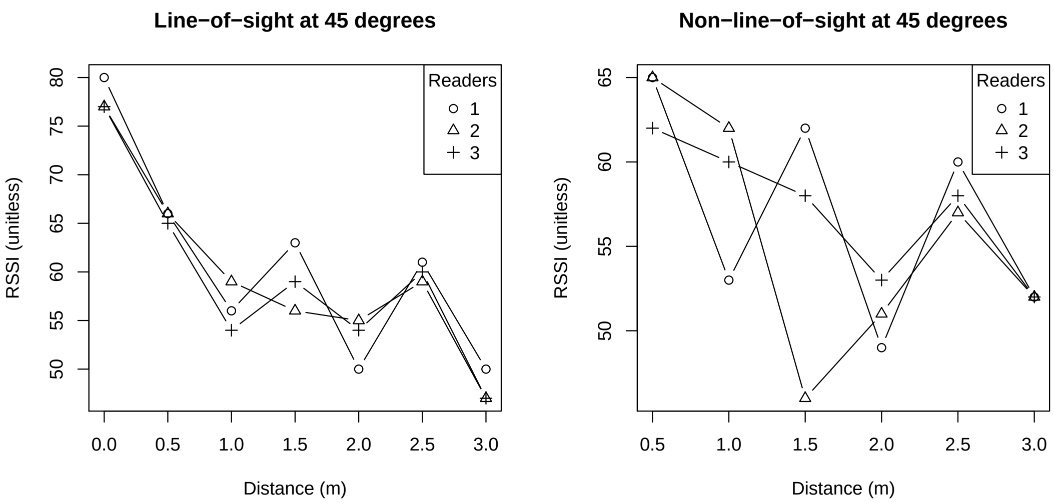


Figure 5.2: Two plots of RSSI measurements at increasing distances with the readers at 45 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

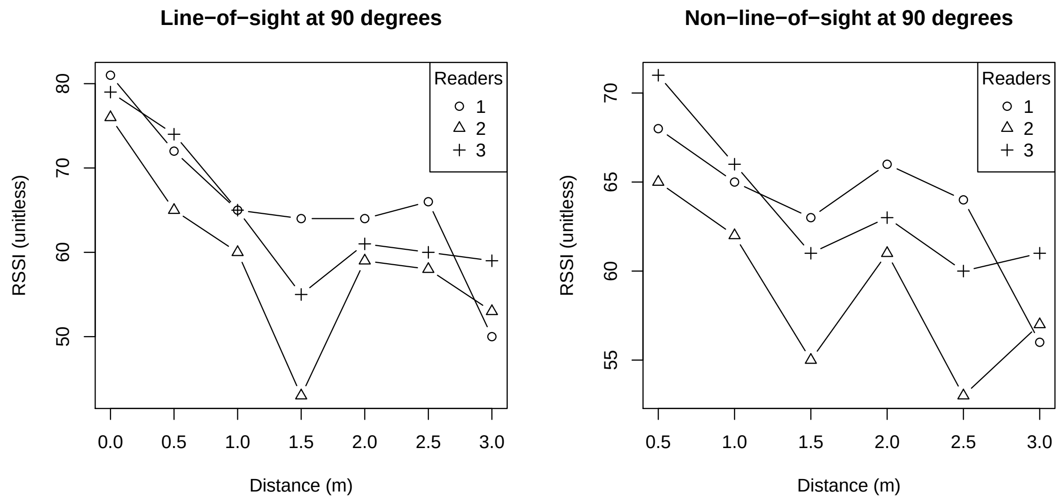


Figure 5.3: Two plots of RSSI measurements at increasing distances with the readers at 90 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

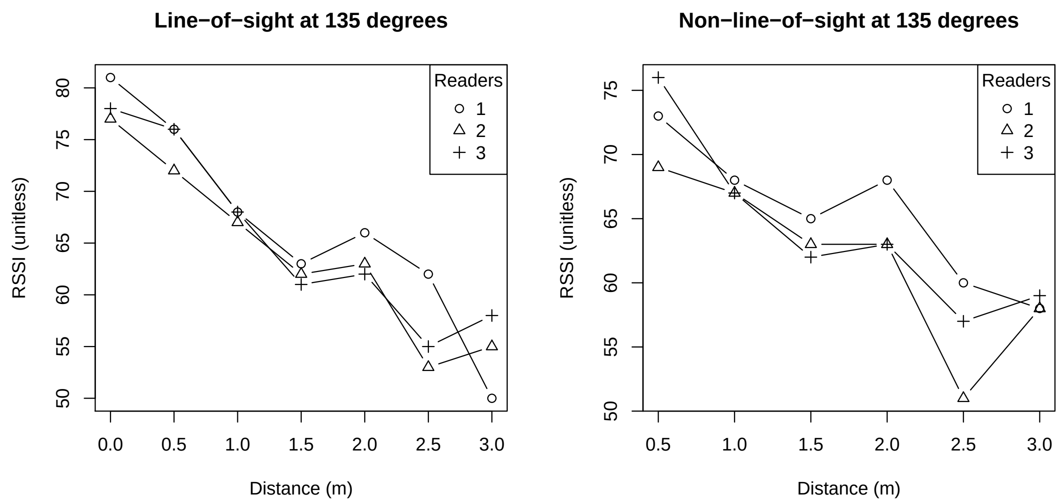


Figure 5.4: Two plots of RSSI measurements at increasing distances with the readers at 135 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

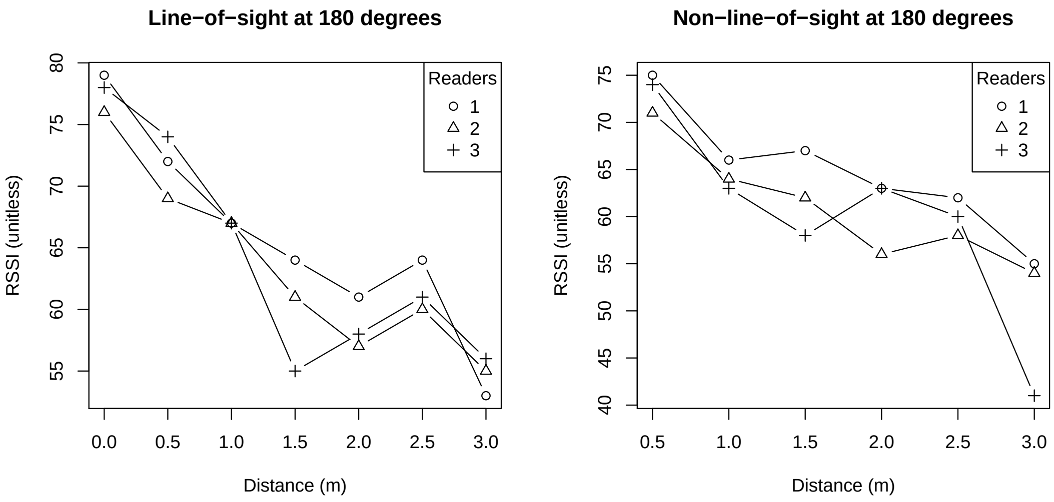


Figure 5.5: Two plots of RSSI measurements at increasing distances with the readers at 180 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

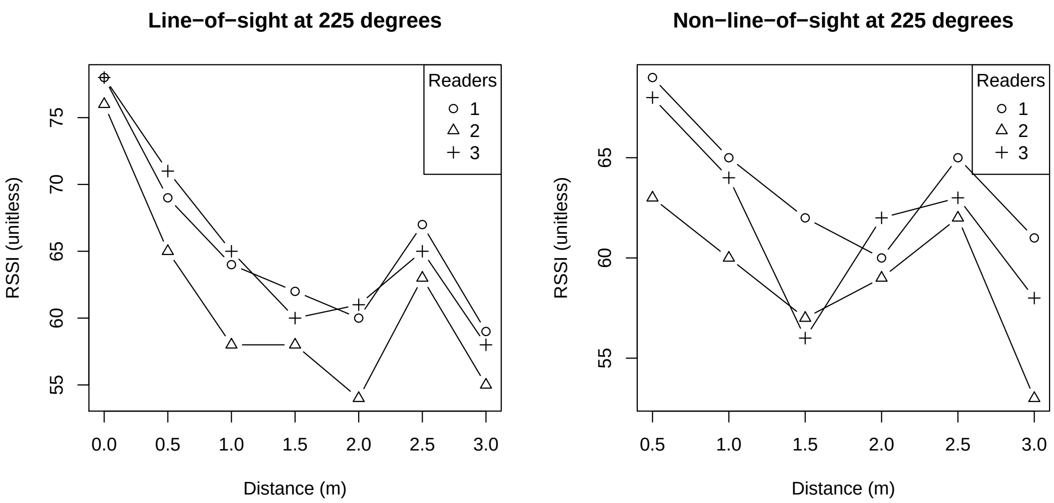


Figure 5.6: Two plots of RSSI measurements at increasing distances with the readers at 225 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

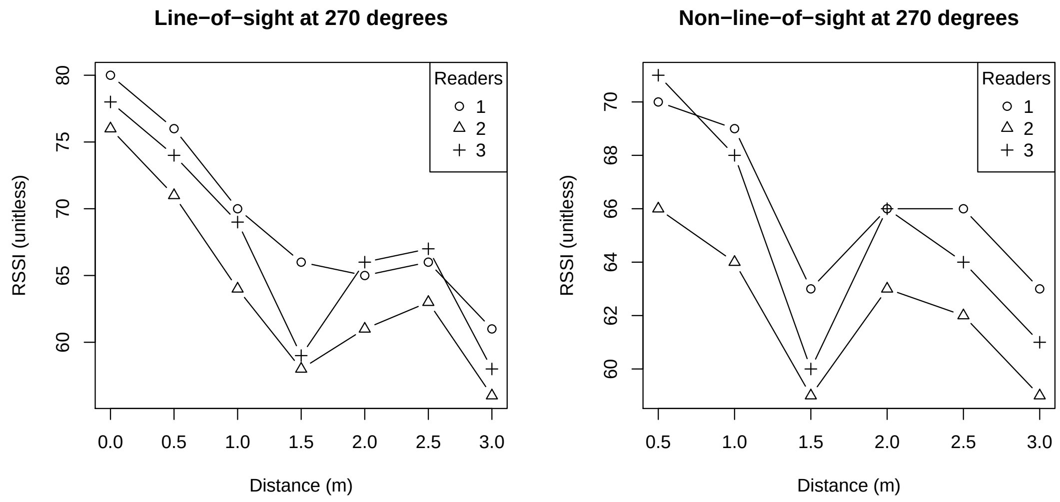


Figure 5.7: Two plots of RSSI measurements at increasing distances with the readers at 270 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

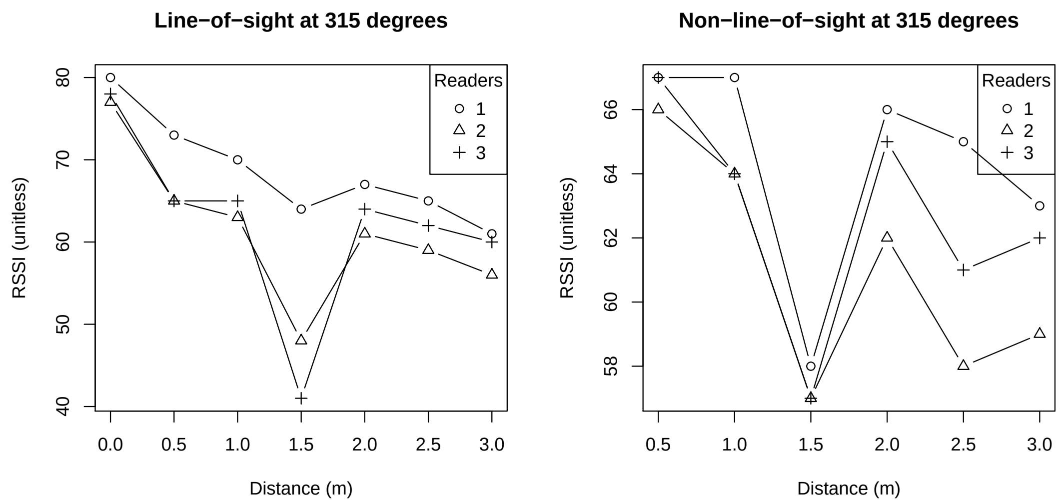


Figure 5.8: Two plots of RSSI measurements at increasing distances with the readers at 315 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

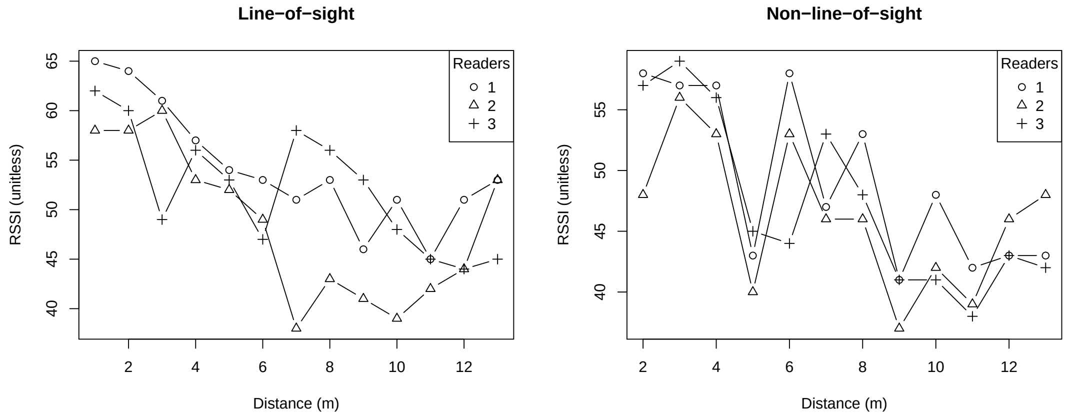


Figure 5.9: Two plots of RSSI measurements at increasing distances with the readers facing the tag. The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle between the reader and the tag).

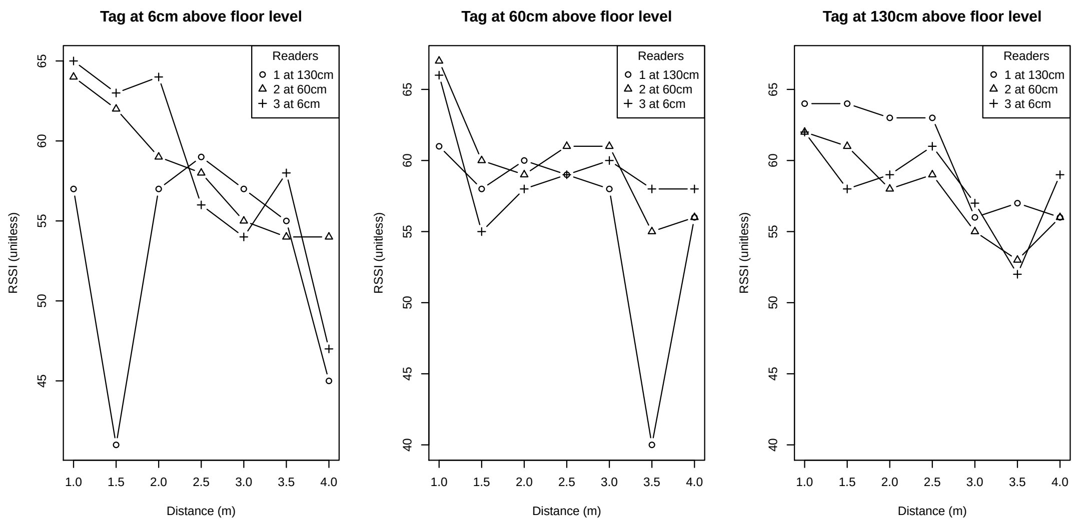


Figure 5.10: Three plots of RSSI measurements at increasing distances with the readers at different elevation from the floor in an indoor environment. The first graph shows how RSSI measurements change as the distance grows when the tag is placed at 6cm above floor level. The second and third graph show the same experiment but the tag is at 60cm and 130cm above the floor level.

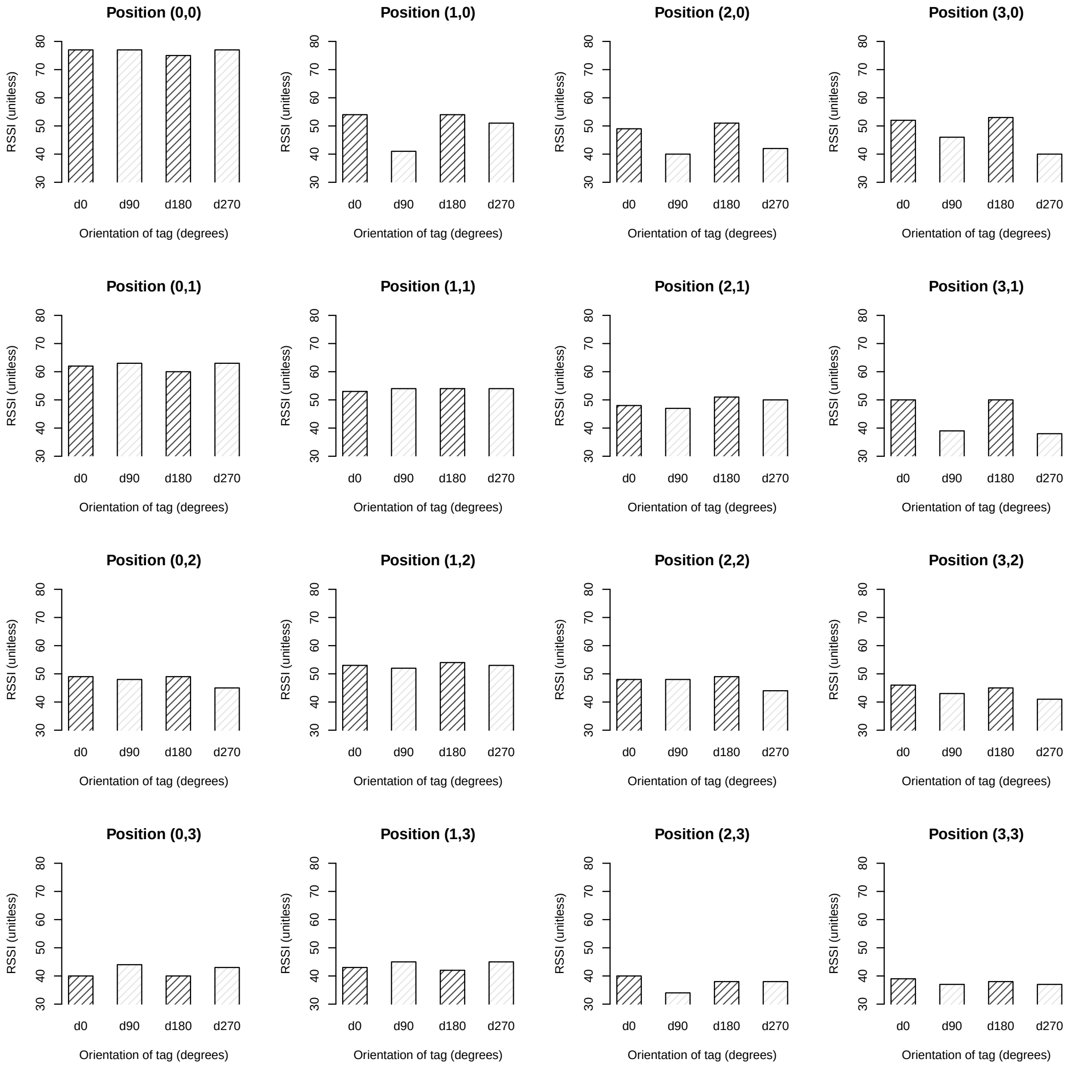


Figure 5.11: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **first** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show the RSSI readings when the tag is facing right (0°), up(90°), left (180°), and down (270°).

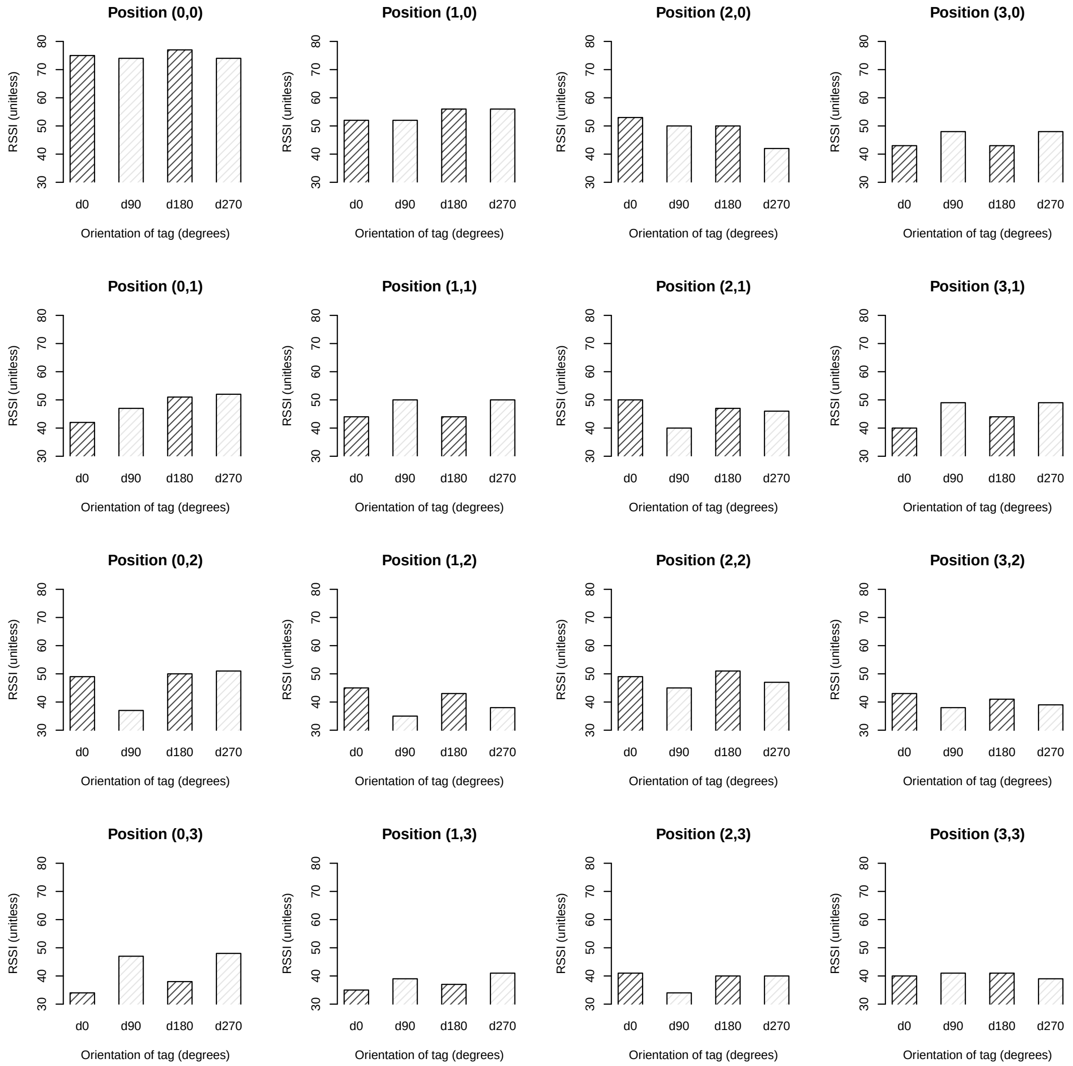


Figure 5.12: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **second** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show the RSSI readings when the tag is facing right (0°), up(90°), left (180°), and down (270°).

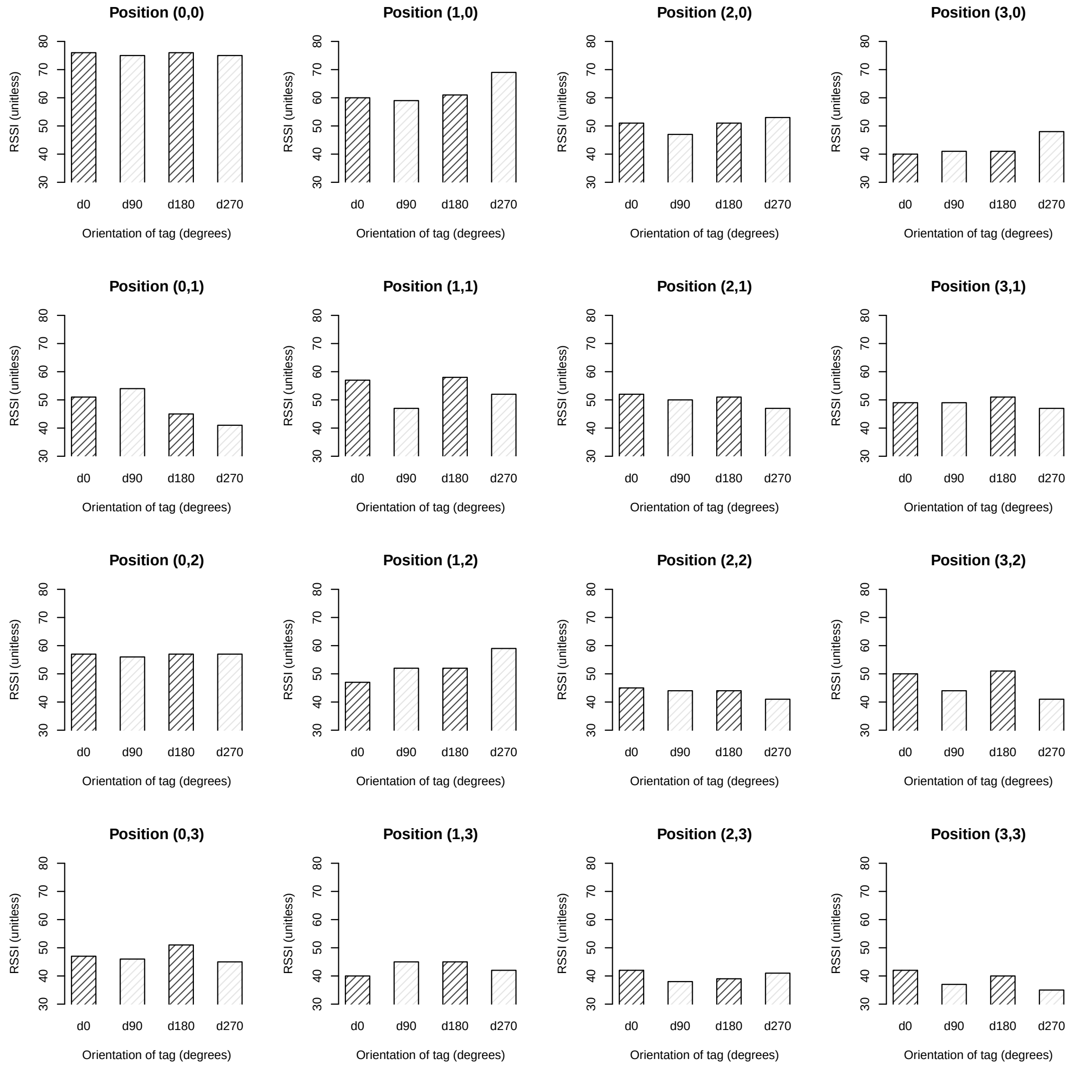


Figure 5.13: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **third** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show the RSSI readings when the tag is facing right (0°), up(90°), left (180°), and down (270°).

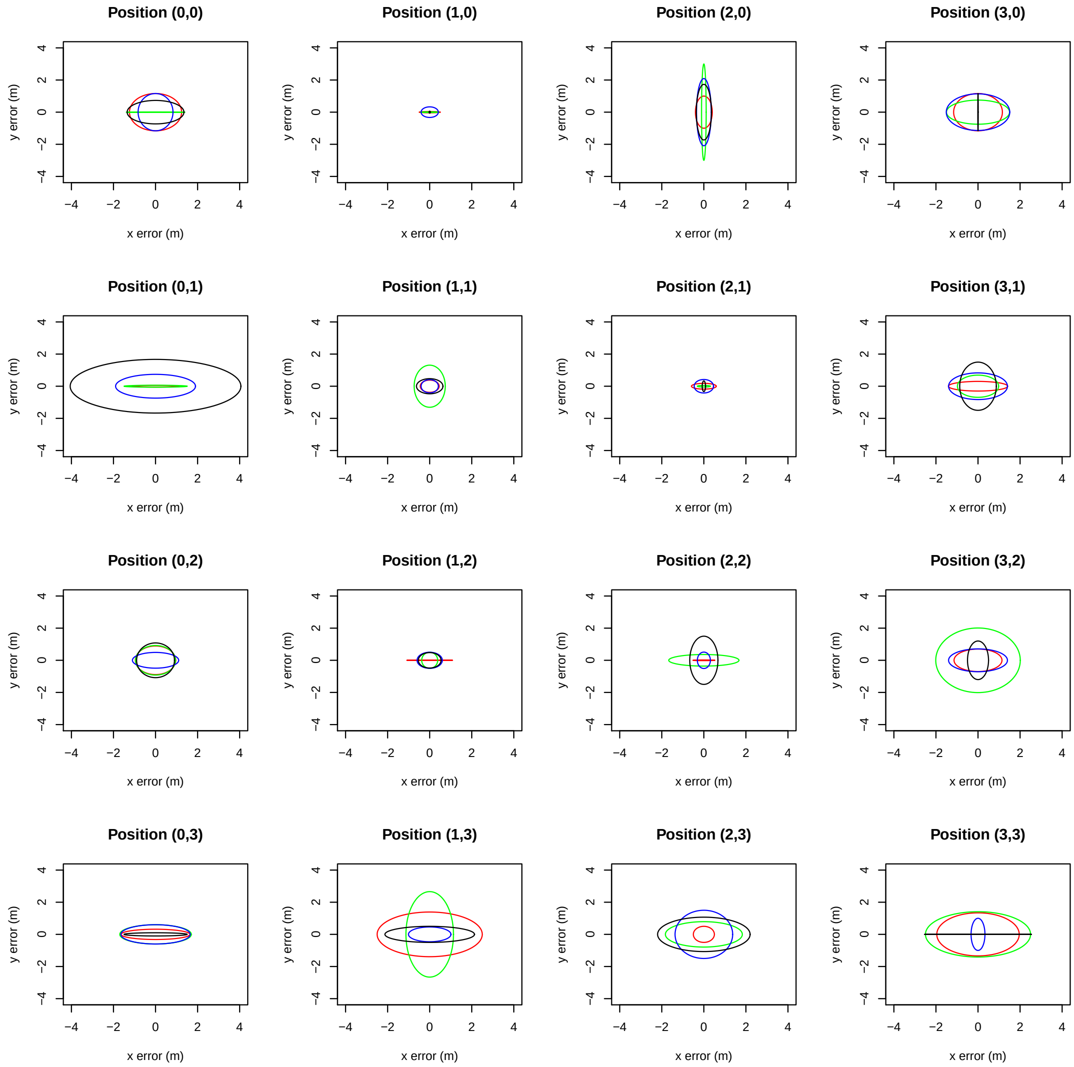


Figure 5.14: Sixteen plots are organised into a four by four grid. The readers are placed at positions (0,0), (0,3), and (3,0). Each plot represents the error in meters between measured and estimated location when the tag is placed at different positions on the grid. Each plot consists of four ellipses that illustrate the x and y error when the tag is facing right (0°), up(90°), left (180°), and down (270°). The colours of the ellipses are red, green, blue, and black, respectively.

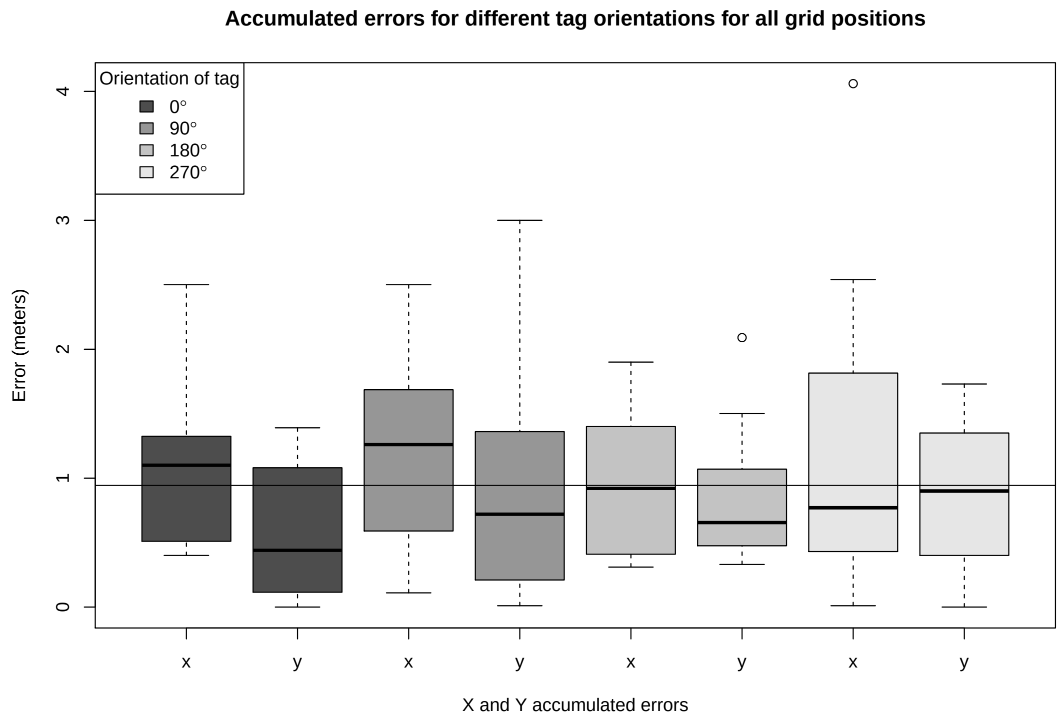


Figure 5.15: A box plot showing errors between measured and estimated locations. The boxes are organised in four groups. Each group consists of errors in the x and y axes for a particular orientation of the tag. The horizontal line across the plot is the mean of all errors regardless of the tag orientation.

Chapter 6

Discussion and Future Work

Chapter 7

Conclusion

Appendix A

Appendix

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