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

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2013

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

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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

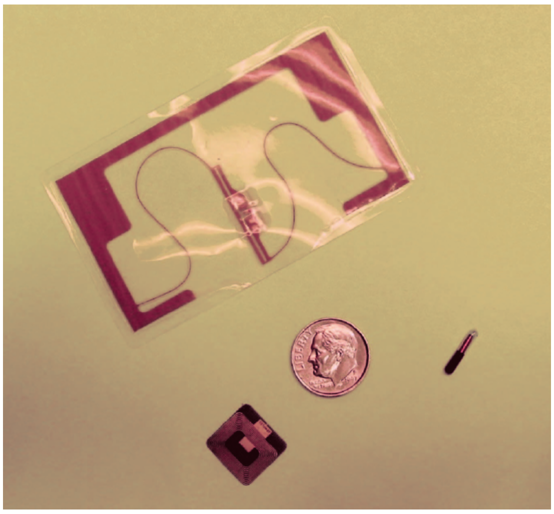


Figure 2.1: Three different variants of RFID tags. Figure from [Want, 2006].

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 is 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.

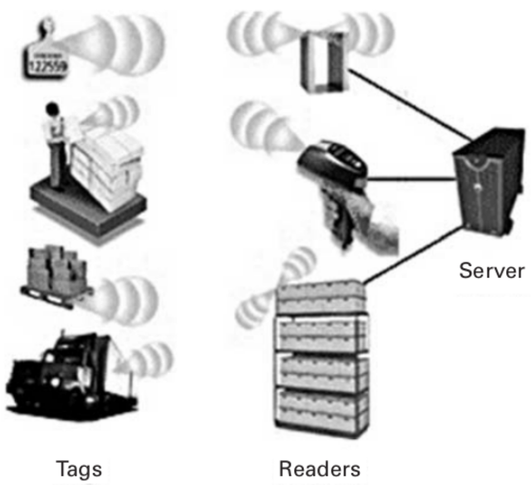


Figure 2.2: Components and applications of RFID. Figure from [Rida et al., 2010, p. 20].

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 a unitless 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 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.

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

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 already is 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 Section 3.3.

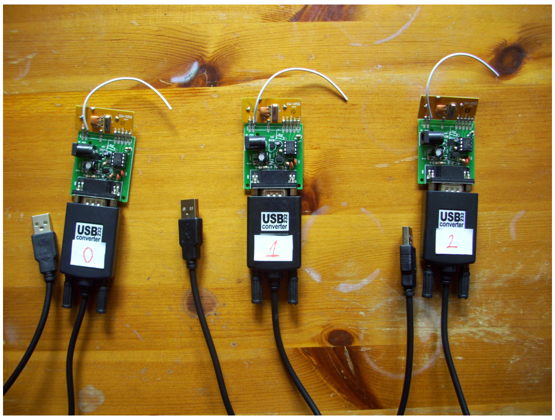
2.3 Project Hardware

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**.

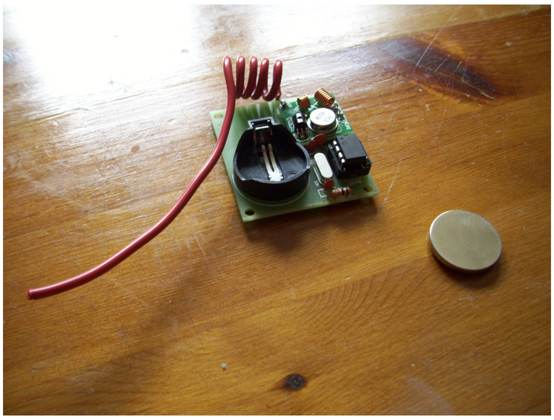
2.3.1 RF9315R-u Active RFID 8 Meters Receiver with RSSI Module

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**.

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 lies in the lower band of Ultra High Frequency (UHF). Such waves propagate mainly by line-of-sight. They are blocked by



(a) Three active RFID readers



(b) One active RFID tag

Figure 2.3: RFID hardware used in this project.

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 are 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.

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 effec-

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.

tively measured between -55 and -115 dBm giving a range of 60 dBm. The readers' 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.

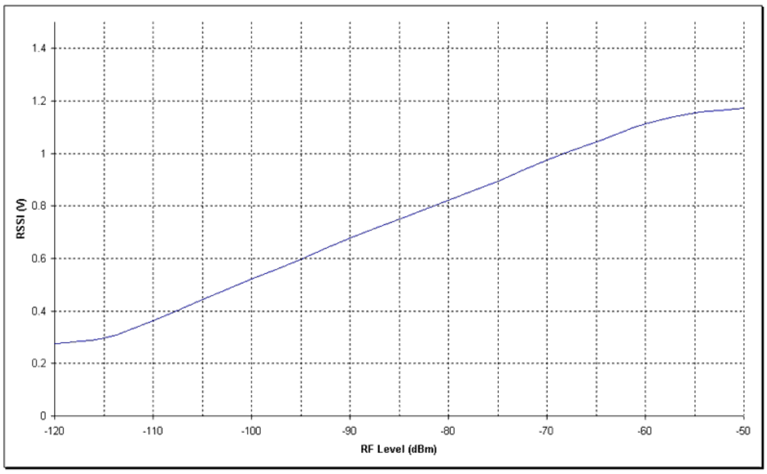


Figure 2.5: A plot of radio frequency signal levels against RSSI voltage. Figure from product website[2].

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 ± 0.5 seconds. Figure 2.3b shows the active RFID tag used 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

[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].

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 eight 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].

[3] Ananiah Electronics active RFID tag - `http://www.ananiahelectronics.com/RF8315T.htm`.

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.

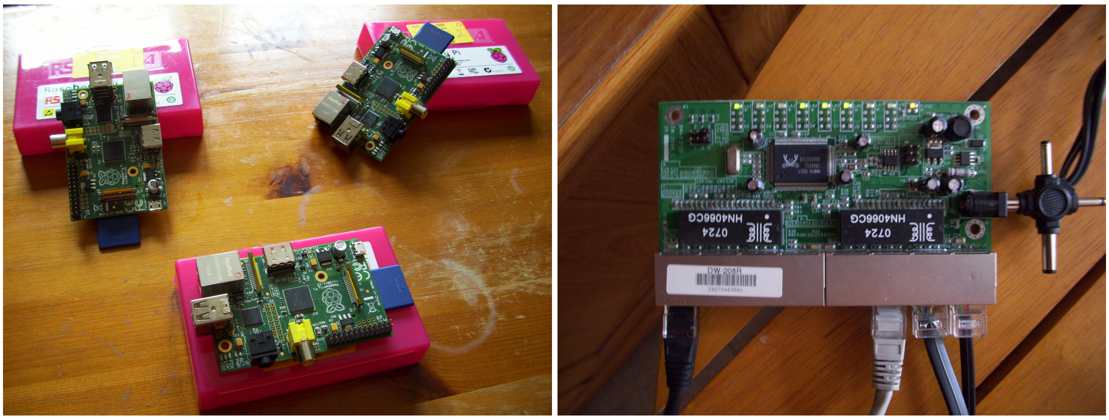
Specification	**Value**
Dimensions	86mm x 54mm
Weight	45g
Power source	5V MircroUSB or GPIO
Power rating	700mA (3.5W)
System on a chip	Broadcom BCM2835
CPU	700MHz ARM1176JZF-S
GPU	Broadcom VideoCore IV 250MHz
Memory	512MB
Storage:	SD card slot
USB 2.0 ports	2
Networking	10/100 Ethernet
Low-level peripherals	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.

[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. Section 3.4 presents the mathematical method for estimating the position of unknown object in three dimensions.

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 five meters for 90 percent of the time, then its accuracy is five 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

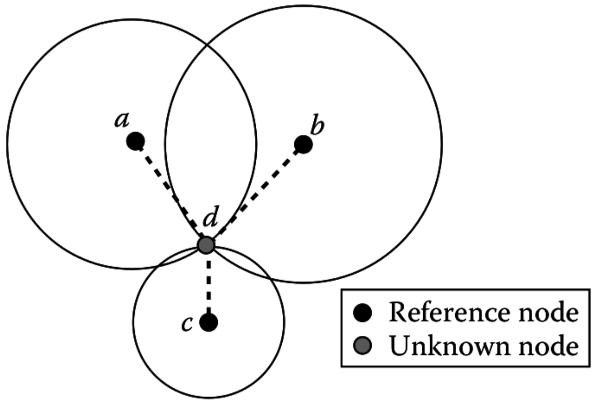


Figure 2.7: The trilateration technique for positioning an unknown node based on distance measurements from three reference nodes. Figure from [Zhang et al., 2009, p. 281].

the system, the density of the infrastructure, and the size of the indoor space. In this work, these metrics are used 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 three meters using off-the-self hardware [Hightower et al., 2000]. Relying on their custom RFID devices, SpotON reported under one 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 four readers and one reference tag per square meter resulting in an average distance error of one 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 three readers, two tracking tags, and 11 reference tags in an 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 ensure an iterative development process, where software components are constructed, debugged, and packaged together, it was decided to use the GIT version control system[1]. 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 merge a number of important changes into versions of the software. In this way, it becomes easy to track and monitor the project progress. The source code and documentation were hosted in a private repository on GITHUB[2] with access granted to the people involved in developing and supervising the project.

3.2 Software Engineering Practices

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

[1] GIT version control system - `http://git-scm.com/`

[2] The private project repository - `https://github.com/sandio/raspi-rfid-tracking`

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 and challenges 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 substituting one class with another.

3.2.3 System scalability

In this project, three single-board computers collaborate by exchanging RFID readings to localise a tagged object. Three reference points are needed in order to use trilateration in two dimensions [Zhang et al., 2009]. Nevertheless, more reader nodes could be used, in case multileration is implemented, to give a better approximation of a tag's position. Another scenario involves nodes disconnecting and later reappearing into the network. These possible cases show the dynamic nature of the system. It could scale up as the system grows, but also scale down if a reader node is faulty. This is an important property of the system, which was noted at the start of the project. To ensure scalability of the server-client model, the multi-threading programming model was used. It allows multiple threads to exist within the context of a single process. As a result, the system could concurrently receive RFID measurements from multiple reader nodes, update data structures, and compute the location of the unknown object.

3.2.4 Documentation

Writing documentation was an important part of this project. The source code of the system has been systematically documented throughout the development process. Using the inline comments specifying how the software components work, an Application Programming Interface (API) was constructed using SPHINX[3], a PYTHON documentation generator. The API contains specifications of data structures, variables, and functions. It is a valuable source of information that provides a quick reference of how the system's components work and interact with each other. In addition, a manual for future users of the system was written. It gives a quick introduction of how to set up and use the system. The API and user manual can be viewed in Appendix **REF TODO**.

This project consists of both hardware and software components. In order to clearly understand how hardware components are connected and how software objects interact, a number of diagrams were used in Chapter **REF** and in the user manual. These diagrams were generated using BLOCKDIAG [4] , a diagram image generator written in PYTHON.

3.3 Converting RSSI to distance

One of the main challenges of this project was to find a reliable way of converting RSSI values into distance from RFID readers to a tag. As discussed in Section 2.2.2, studies have shown that RSSI is not a reliable or accurate measure of distance. Nevertheless, RSSI is one of the main parameters of this system and distance estimation is solely based on it.

3.3.1 Free-space Path Loss

The first attempt to provide a conversion between RSSI and distance was relying on the inverse-square physical law and free-space path loss (FSPL) formula. In free space propagation, electromagnetic waves obey the inverse-square law stating that the intensity of the emitted radiation is inversely proportional to the square of the distance from the source of the emitted radiation [Schlaikjer and Westman, 1962, p. 19]. This can be expressed as the following relation:

[3] SPHINX - a Python documentation generator - `http://sphinx-doc.org/index.html`

[4] BLOCKDIAG - simple diagram images generator - `http://blockdiag.com/en/`

$$Intensity \propto \frac{1}{distance^2}$$

A more complete relationship between signal strength and distance is given by the FSPL formulation. Free-space path loss is the loss in signal strength of an electromagnetic wave propagating through free space without any obstacles [Balanis, 2012]. FSPL is proportional to the square of both distance and frequency of the radio signal. It can be expressed in terms of decibels given distance in meters and radio frequency in megahertz[5]:

$$FSPL(dB) = 20\log_{10}(d_{meters}) + 20\log_{10}(f_{MHz}) - 27.55$$

Rearranging the terms of the equation to find the distance gives:

$$d_{meters} = 10^{(FSPL(dB) - 20\log_{10}(f_{MHz}) + 27.55)/20}$$

Section 2.2.1 discussed the relationship between RSSI and received signal strength (RSS). RSSI is a unitless measurement derived from the values of the RSS. In Section 2.3.1, Figure 2.5 shows the relationship between RSSI and RSS for the RFID receivers used in this project. Consequently, RSSI values can be converted to received signal strength expressed in dBm and inserted into the equation above as $FSPL(dB)$. The frequency of the RFID project hardware is $315MHz$ (see Table 2.2 and 2.3).

There are three problems with this approach. First, it models how the signal strength decreases in a line-of-sight propagation in a free from obstacles environments. This project is concerned with location sensing in indoor spaces making the free-space path loss formula inappropriate for this setting. Second, computing the distance for the minimum ($0dB$) and maximum ($60dB$) values of the signal strength range results in distances 0.075 and 75.716 meters, which is beyond the practical range of the RFID devices. Third, the conversion from RSSI to RSS might not be appropriate in this case. The RFID equipment for this project is more affordable compared to commercial RFID equipment[6]. As a result, the online support and specifications are scarce, which raises the question to what extent these can be trusted. Moreover, the manufacturer claims a RSSI resolution of eight bits outputting values between 0 and 255. During the range experiments with this hardware a much smaller resolution was recorded. Consequently, converting RSSI unitless values to received signal strength in dBm cannot be relied upon. For details on the evaluation of the RFID devices refer to **REF**.

3.3.2 Translation table

Rather than relying on the physical relationship between electromagnetic waves and distance, a simpler and more direct approach was taken. For each RFID reader, a translation table was constructed mapping RSSI to distance. According to the manufacturer, but also observed in hardware experiments, reader measurements vary between different devices. There are two reasons for this. First, the RFID readers are

[5] Derivation the dB version of the FSPL equation - `http://www.ece.uvic.ca/~peterd/35001/ass1a/node1.html`

[6] How much do RFID readers cost today? - `http://www.rfidjournal.com/faq/show?86`

handmade, which introduces small differences in their circuits. Second, the devices are not calibrated to each other when being built.

The methodology for constructing these translation tables relies entirely on RSSI measurements collected while evaluating the RFID devices. A number of experiments were conducted testing how RSSI changes as the distance between a reader and tag increases. In order to account for the characteristics of indoor environments, these experiments have taken into account the orientation of the tag to the reader, line-of-sight propagation versus obscuring the tag with an obstacle, and elevation of the tag to the reader. Combining measurements from different experiments gives a more realistic representation of how RSSI changes in an indoor environment. Table 3.1 presents the translation table constructed for the first reader. Similar tables were developed for the other two devices (see Appendix A.1).

Distance	0	1	1	2	2	3	3	4	4	5	5	6	6	7
RSSI	80	65	64	62	61	57	56	53	52	48	47	46	45	44

Table 3.1: RSSI value ranges used to estimate distance when using the first reader.

As an example, the first two columns of Table 3.1 have the following meaning. When the reader and tag antennas were touching the average RSSI value from all experiments was 80. When the tag was one meter away from the reader, the average RSSI value of all experiment measurements was 65. RSSI values between 80 and 65 are linearly converted to the new range from zero to one meters as follows:

$$Old.range = old.min - old.max$$

$$New.value = new.min + (old.min - old.value)/old.range$$

An obvious limitation of these conversions is the size of the RSSI ranges. For example, there are 15 possible values that the first reader could measure when the tag is between zero and one meters away from it. In contrast, for a distance between six and seven meters the RSSI values change only by one unit. Following from that, the granularity of the distance estimation changes depending on the range of the RSSI measurements. This is caused by a hardware limitation of the readers when measuring RSSI and has been found during the range experiments presented in **REF**.

There is another factor contributing to the accuracy of this conversion. The RFID tag is using a battery for its power supply. During continuous operation the battery power level gradually drops, thus the tag emits a weaker radio signal as the battery is being depleted. This is reflected in the RSSI measurements making the translation tables inaccurate. In order to account for the RSSI changes, the incoming measurements were increased by an integer factor chosen based on observation. Different factors were selected for each reader due to their measurement differences.

In summary, this conversion method is not universal and probably cannot be applied to other brands of RFID devices. There are numerous factors that contribute to the variations in RSSI such as radio signal reflection, multi-path fading, and shadowing, to name a few. Nevertheless, this method was selected to translate RSSI to distance. Once the translation tables are constructed, it is a matter of calibration. As mentioned above, RSSI to distance conversion is one of the main variables of this system. How these translation tables performed is discussed in Section **REF**, where the evaluation results of the system in terms of localisation accuracy are presented.

3.4 Trilateration

Trilateration is a localisation method computing the position of an unknown object based on range measurements from three reference points at known locations. The concept of this technique was described in Section 2.4.1. This section presents the mathematical technique used in this project that provides an exact and computationally efficient solution for three-dimensional position estimation. The solution is based on the work of Manolakis [Manolakis, 1996] and the Wikipedia article on trilateration [Wikipedia, 2013].

3.4.1 Special case

In three-dimensional Cartesian coordinate system, the equations for three spheres are:

$$\begin{aligned} r_1^2 &= (x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 \\ r_2^2 &= (x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 \\ r_3^2 &= (x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 \end{aligned}$$

where the sphere centres are $\vec{p}_1 = (x_1, y_1, z_1)$, $\vec{p}_2 = (x_2, y_2, z_2)$, $\vec{p}_3 = (x_3, y_3, z_3)$ and r_1, r_2, and r_3 are the sphere radii. Solving these equations for x, y, and z would give their intersection point. However, this is hard to do directly. In order to simplify the calculations, a special case is defined that later can be used as the basis for a general solution. There are three requirements of the special case. First, the three centres of the spheres are on the $z = 0$ plane, hence working in two dimensions. Second, one of the centres of the spheres, $\vec{p}_1$, is located at the origin. Third, another centres of the spheres, $\vec{p}_2$, is on the x-axis, thus two of the spheres are collinear. The equations for the three spheres can be rewritten as follows:

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

$$r_2^2 = (x-d)^2 + y^2 + z^2 \tag{3.2}$$

$$r_3^2 = (x-i)^2 + (y-j)^2 + z^2 \tag{3.3}$$

where d is the distance between sphere centres $\vec{p}_1$ and $\vec{p}_2$ and i and j are the signed magnitudes of the x and y components of the vector from $\vec{p}_1$ to $\vec{p}_3$. Figure 3.1 illustrates these components and the positions of the spheres in the $z = 0$ plane.

To solve these equations, first subtract 3.2 from 3.1 and solve for x:

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

Next, subtract 3.3 from 3.1 and solve for y:

$$y = \frac{r_1^2 - r_3^2 + i^2 + j^2}{2j} - \frac{i}{j}x$$

Finally, use 3.1 to solve for z:

$$z = \pm\sqrt{r_1^2 - x^2 - y^2}$$

These three equations provide the coordinates of the intersection point (x, y, z) of the three spheres.

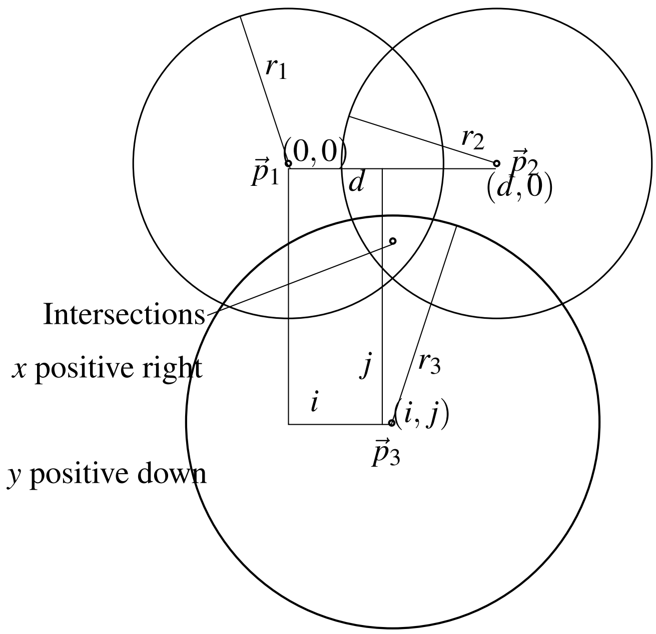


Figure 3.1: Figure showing three intersecting spheres in the plane containing their centres. Figure from [Wikipedia, 2013].

3.4.2 General solution

The solution of the aforementioned case cannot be applied in a general three-dimensional case because its requirements are not met. This is overcome by treating the sphere centres, $\vec{p}_1$, $\vec{p}_2$, and $\vec{p}_3$, as vectors from the origin:

$$\begin{aligned}
\vec{p}_1 &= (x_1, y_1, z_1) \\
\vec{p}_2 &= (x_2, y_2, z_2) = \vec{p}_1 + \hat{e}_x d \\
\vec{p}_3 &= (x_3, y_3, z_3) = \vec{p}_1 + \hat{e}_x i + \hat{e}_y j
\end{aligned}$$

where $\hat{e}_x$, $\hat{e}_y$, and $\hat{e}_z$ are the basis unit vectors in the x, y, and z original coordinate system; d, i, and j are the same variables defined above. The unit vectors and variables are expressed as follows:

$$d = \|\vec{p}_2 - \vec{p}_1\|, \qquad i = \hat{e}_x \cdot (\vec{p}_3 - \vec{p}_1), \qquad j = \hat{e}_y \cdot (\vec{p}_3 - \vec{p}_1)$$
$$\hat{e}_x = \frac{\vec{p}_2 - \vec{p}_1}{d}, \qquad \hat{e}_y = \frac{\vec{p}_3 - \vec{p}_1 - \hat{e}_x i}{\|\vec{p}_3 - \vec{p}_1 - \hat{e}_x i\|}, \qquad \hat{e}_z = \hat{e}_x \times \hat{e}_y$$

Thus, the intersection point of the three spheres, which is the solution of the problem, is:

$$\vec{p}_{1,2} = \vec{p}_1 \ + \ \hat{e}_x x \ + \ \hat{e}_y y \ \pm \hat{e}_z z$$

This mathematical method is used to estimate the position of an RFID tag. It is efficient because trigonometric functions are not used. Instead, this method relies on elementary arithmetic operations [Manolakis, 1996]. When implementing this method, one needs to account for some specific cases, for instance, when d equals 0. In this case, the sphere centres $\vec{p}_1$ and $\vec{p}_2$ share the same coordinates, which means that these two spheres are concentric. Consequently, no solution to the problem exists because these spheres cannot intersect when they have different radii and are the same sphere if they have equal radii. Section **REF** is concerned with the implementation details and conditions guarding for specific cases.

Chapter 4

Design and Implementation

4.1 Summary

Chapter 5

Evaluation

5.1 Summary

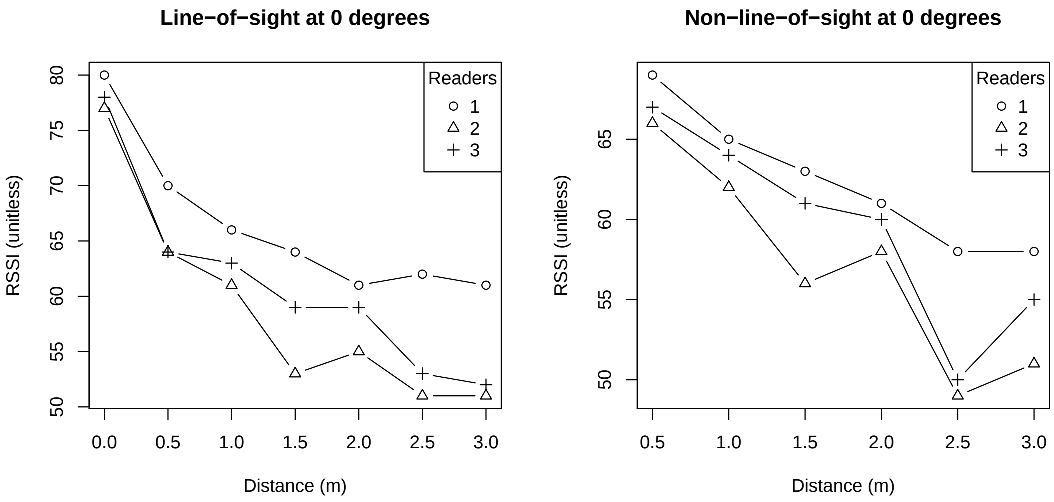


Figure 5.1: Two plots of RSSI measurements at increasing distances with the readers at 0 degrees (antennas facing the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation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

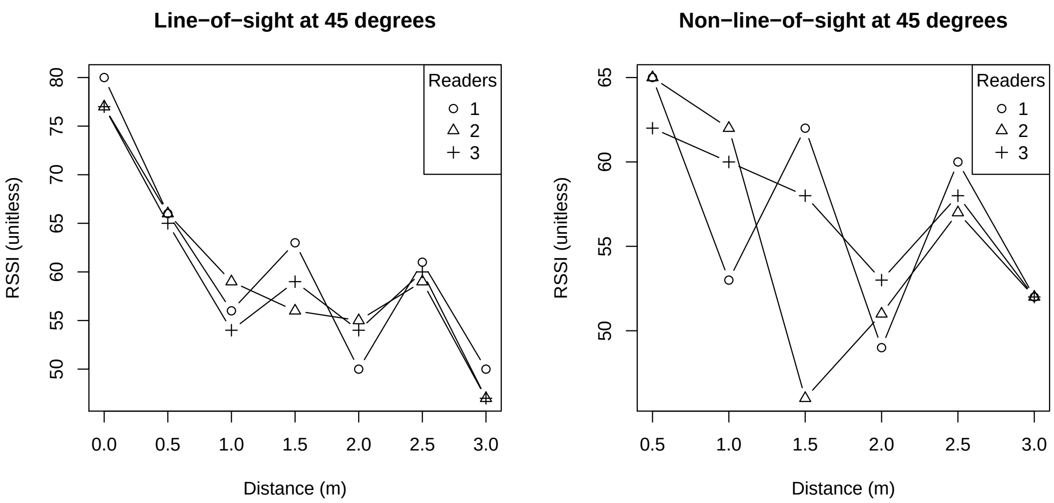


Figure 5.2: Two plots of RSSI measurements at increasing distances with the readers at 45 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

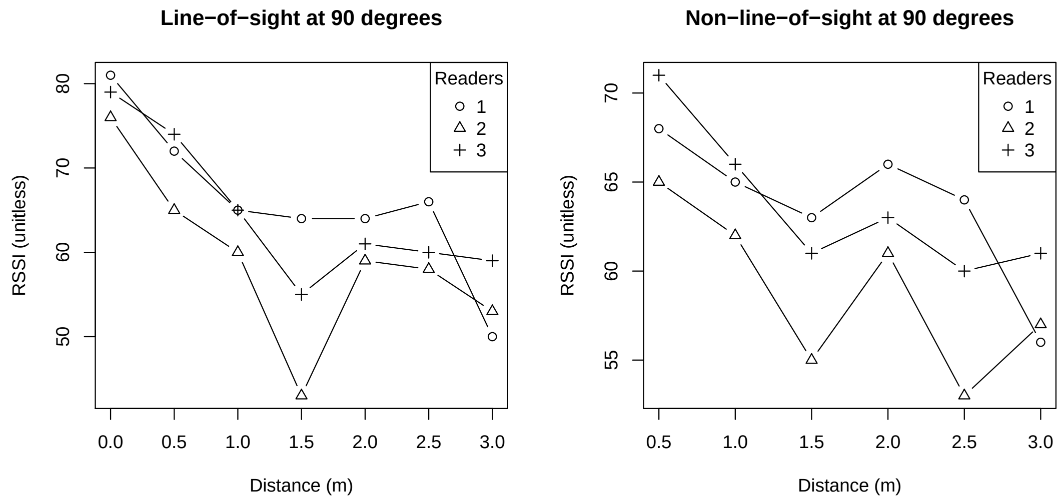


Figure 5.3: Two plots of RSSI measurements at increasing distances with the readers at 90 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

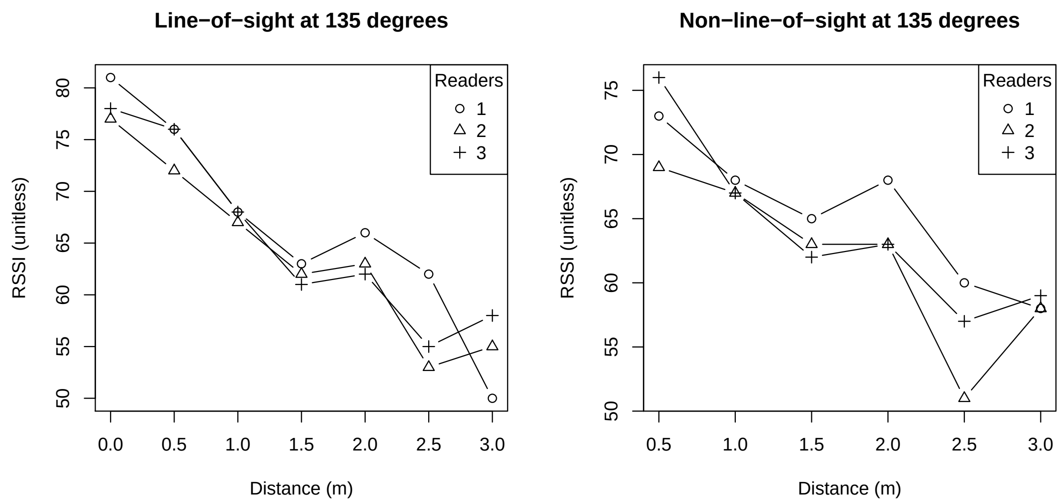


Figure 5.4: Two plots of RSSI measurements at increasing distances with the readers at 135 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

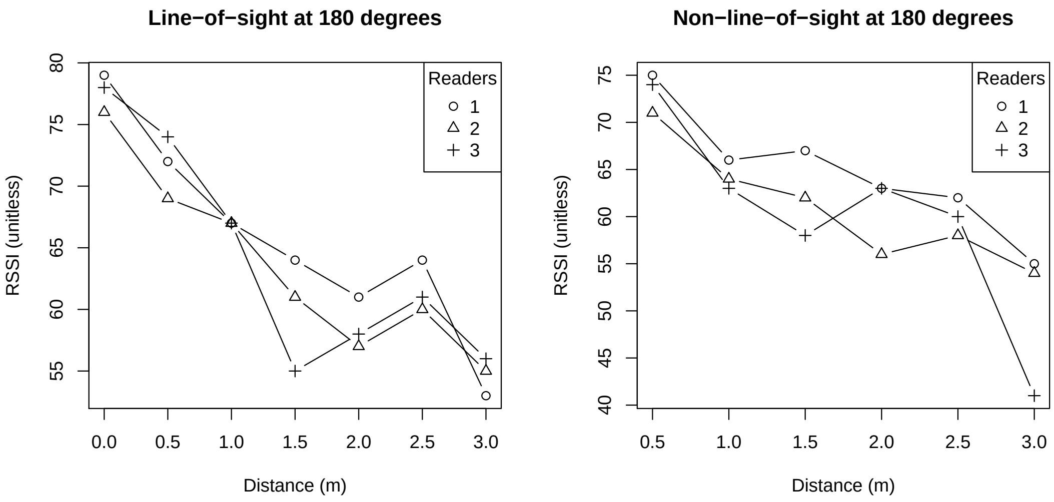


Figure 5.5: Two plots of RSSI measurements at increasing distances with the readers at 180 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

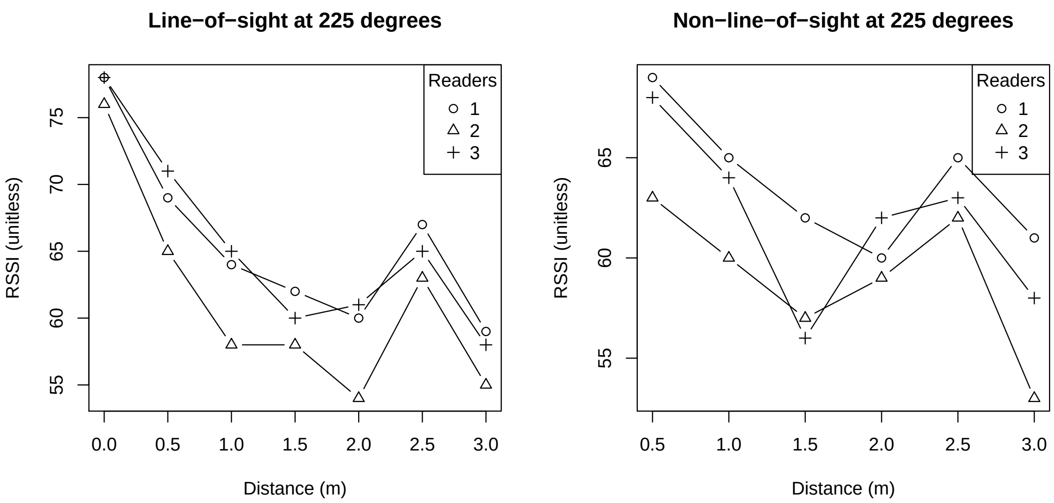


Figure 5.6: Two plots of RSSI measurements at increasing distances with the readers at 225 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

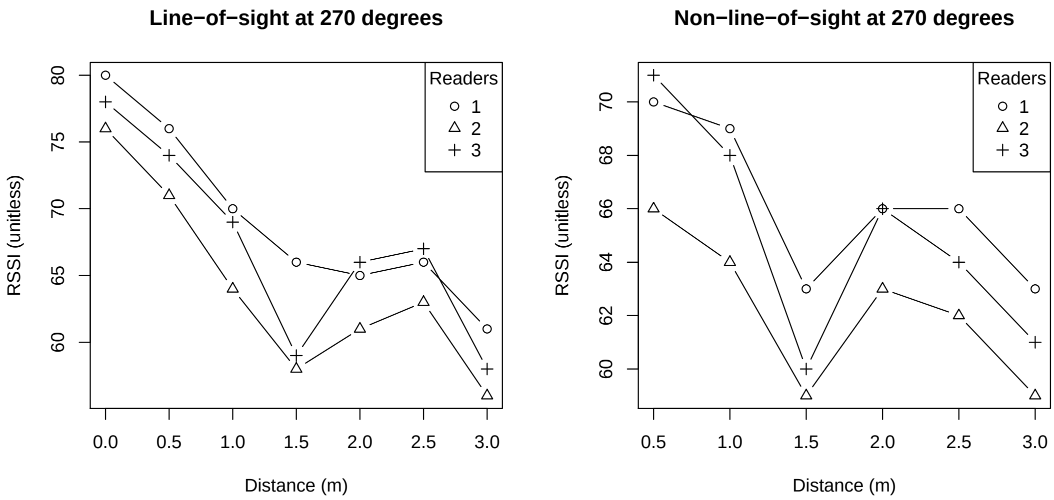


Figure 5.7: Two plots of RSSI measurements at increasing distances with the readers at 270 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

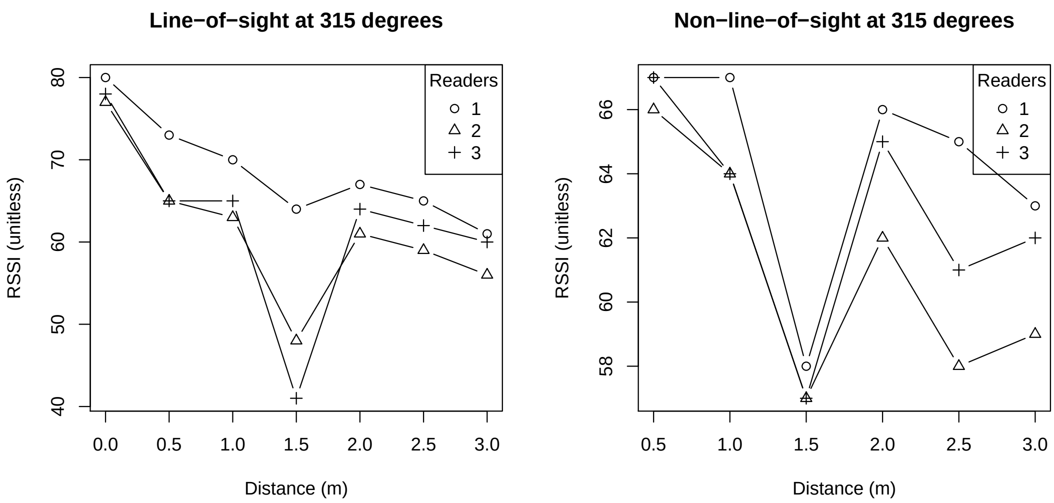


Figure 5.8: Two plots of RSSI measurements at increasing distances with the readers at 315 degrees (antennas at an angle to the tag). The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal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

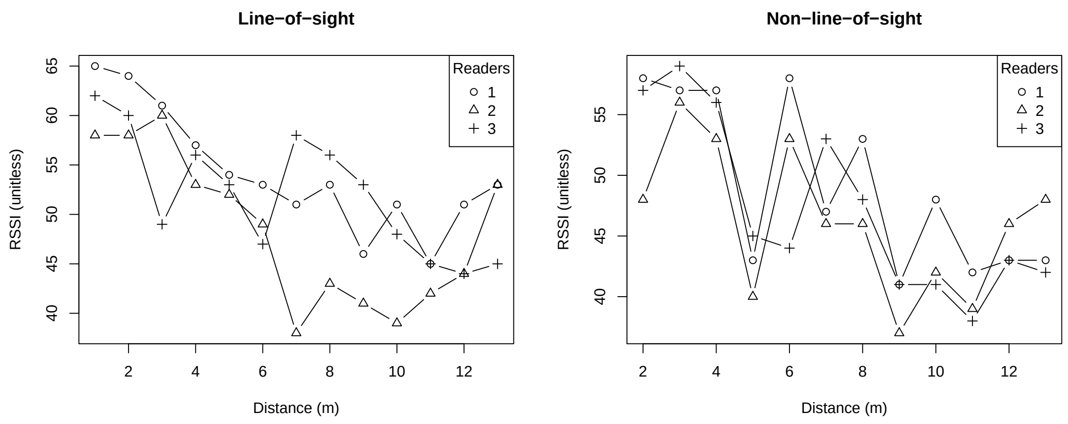


Figure 5.9: Two plots of RSSI measurements at increasing distances with the readers facing the tag. The left graph show how RSSI values change with a line-of-sight signal propagation. The right graph illustrates the same experiment but with a non-line-of-sight signal propagation (there is an obstacle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

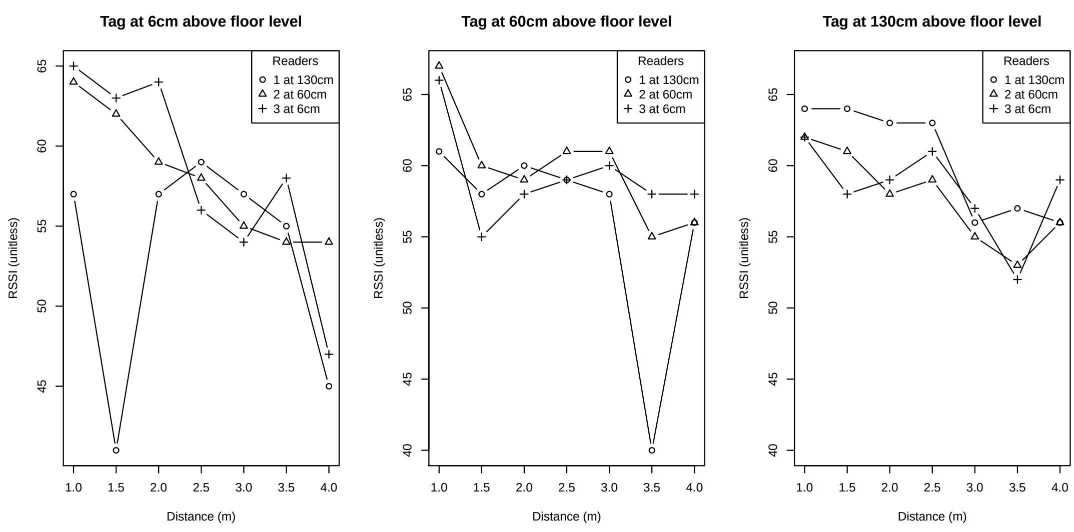


Figure 5.10: Three plots of RSSI measurements at increasing distances with the readers at different elevation from the floor in an indoor environment. The first graph shows how RSSI measurements change as the distance grows when the tag is placed at 6cm above floor level. The second and third graph show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

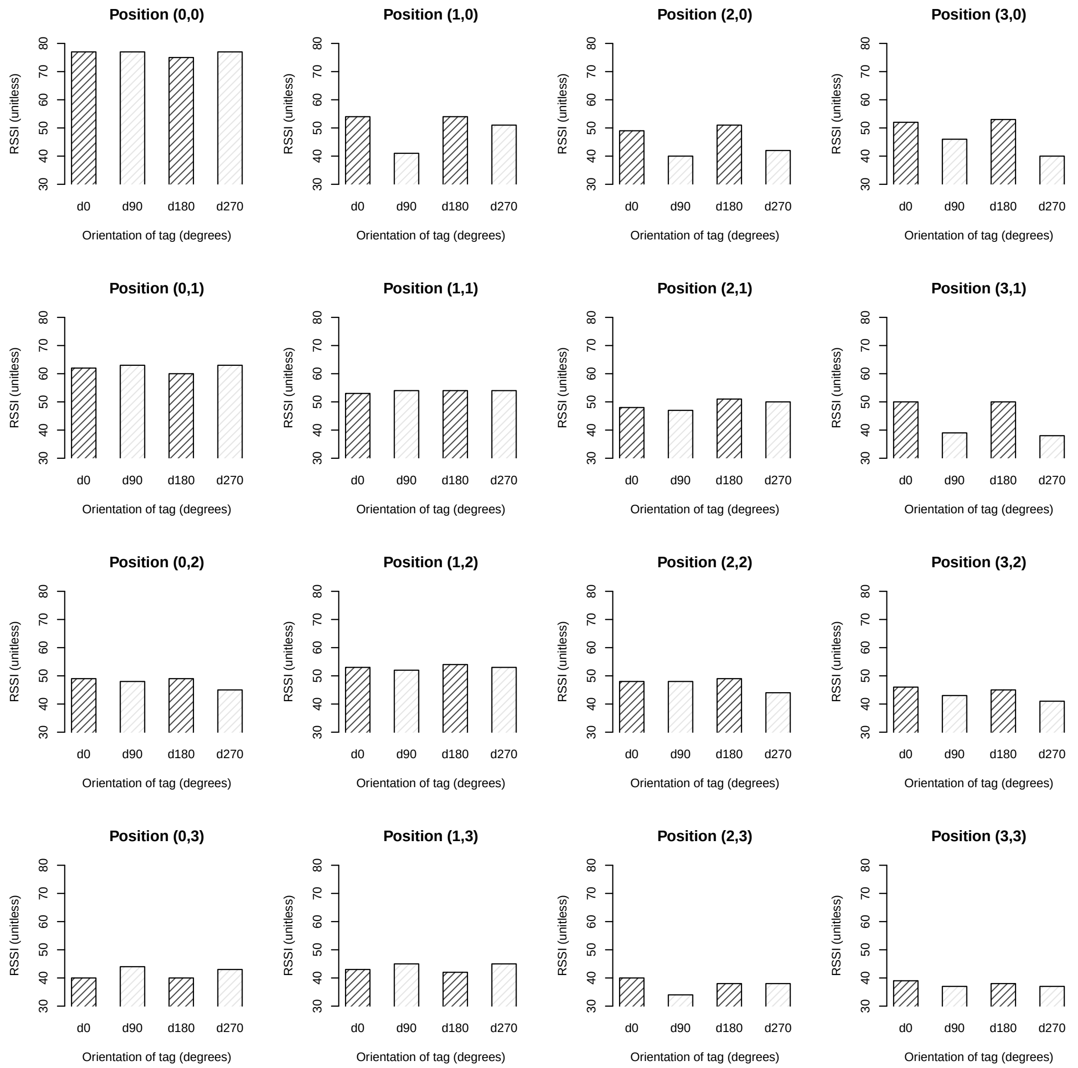


Figure 5.11: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **first** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show the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

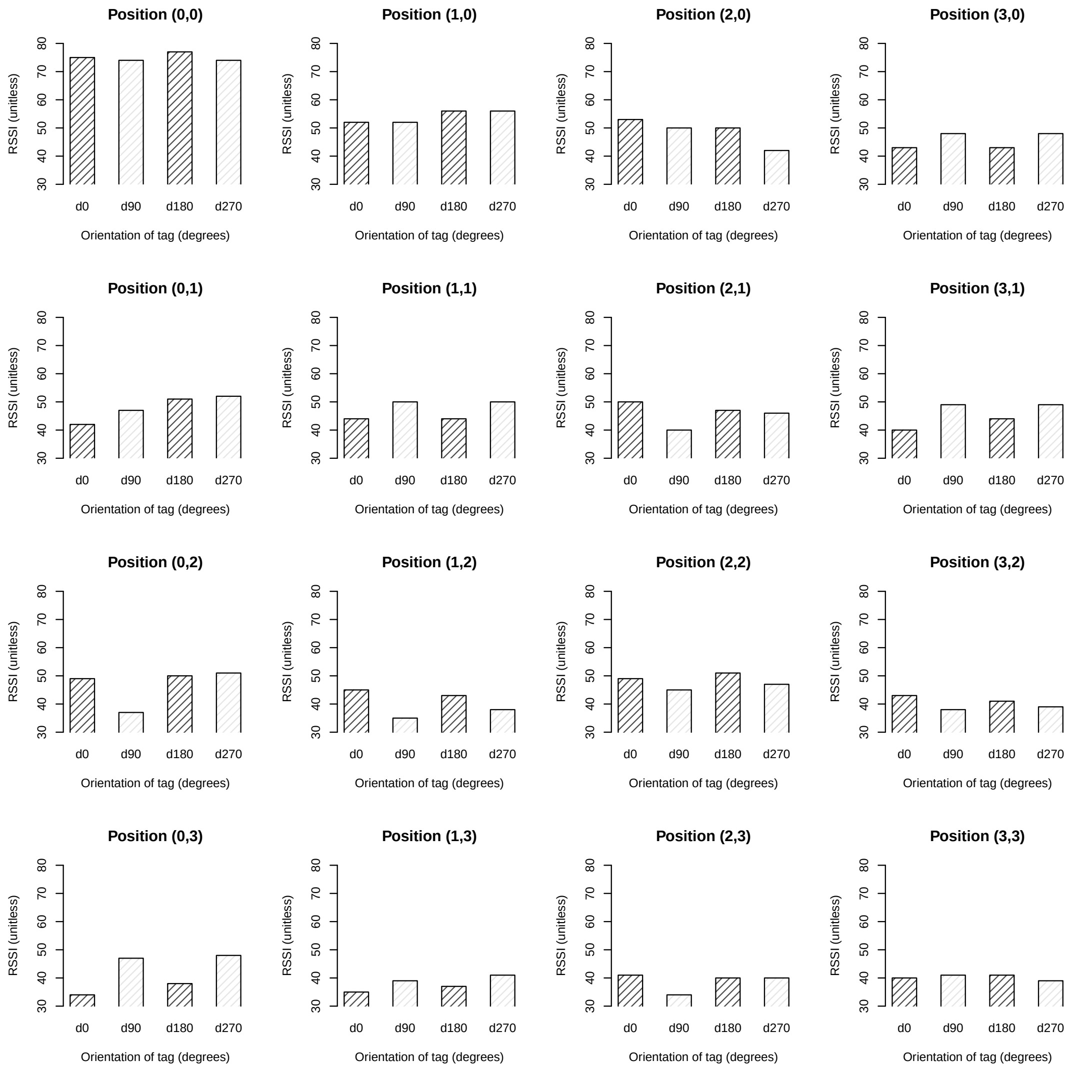


Figure 5.12: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **second** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show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

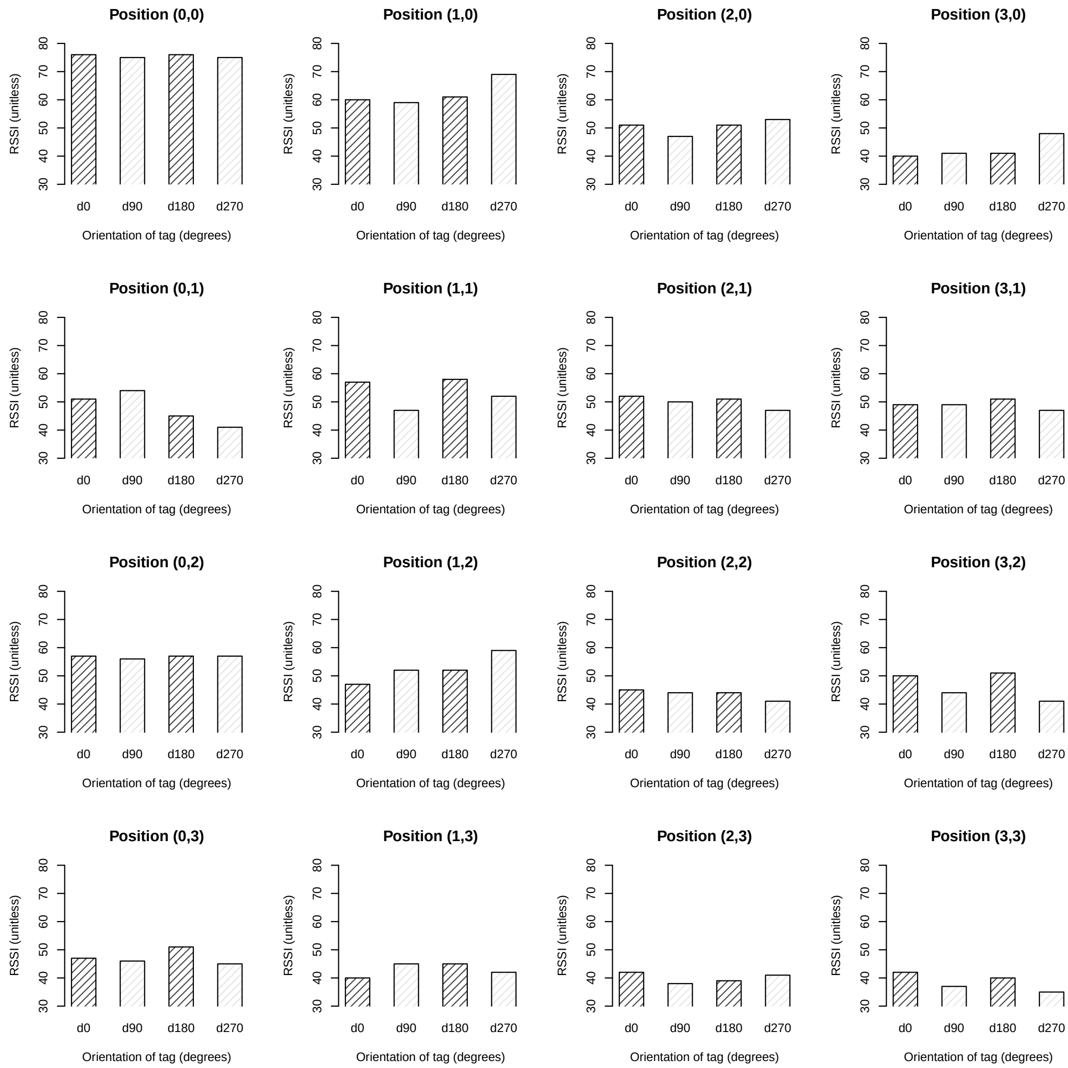


Figure 5.13: Sixteen plots are organised into a four by four grid. Each plot represents the RSSI measurements of the **third** reader when the tag is placed at different positions on the x and y axes of the grid. The positions of the tag are all measured in meters. Every four bars in each plot show the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

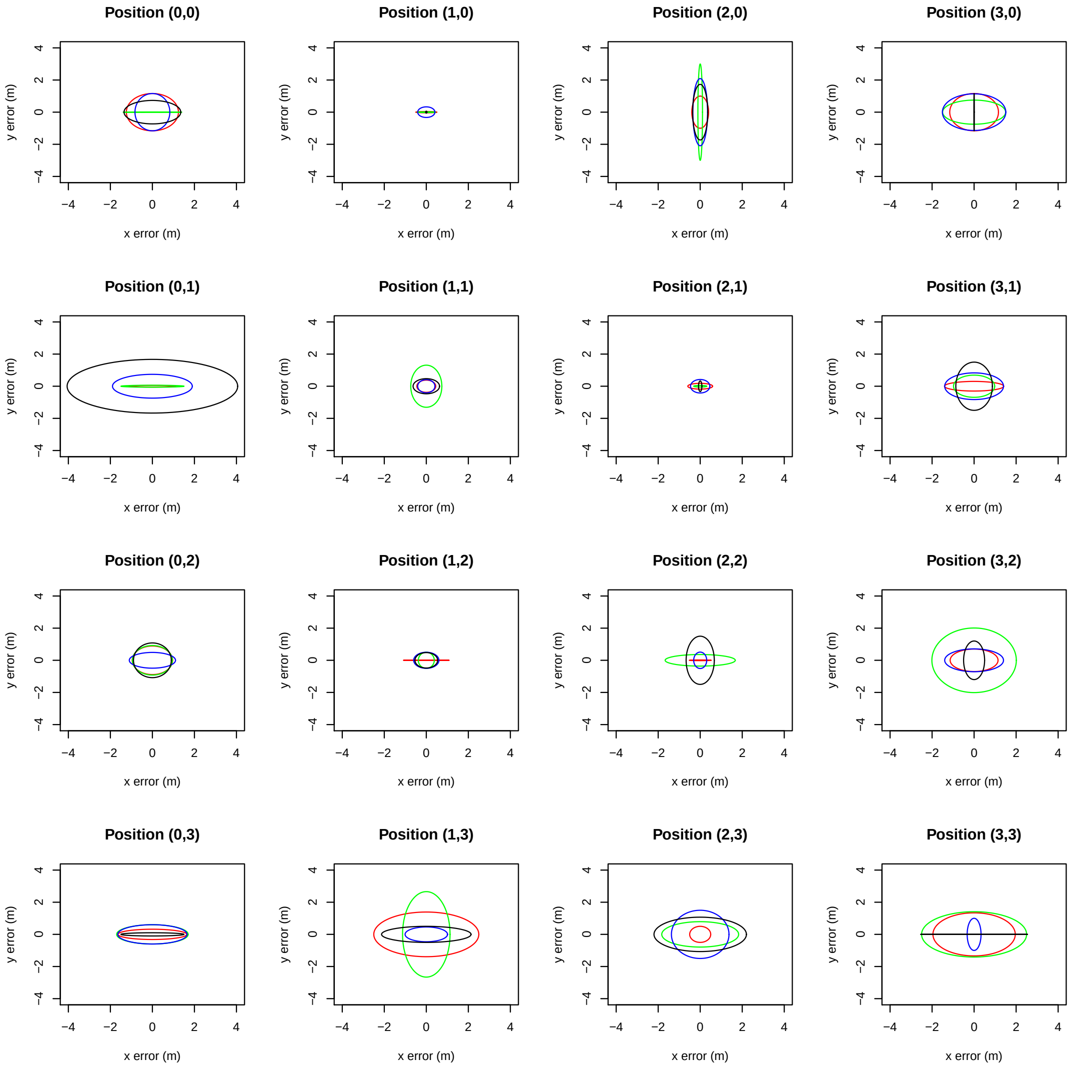


Figure 5.14: Sixteen plots are organised into a four by four grid. The readers are placed at positions (0,0), (0,3), and (3,0). Each plot represents the error in meters between measured and estimated location when the tag is placed at different positions on the grid. Each plot consists of four ellipses 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.

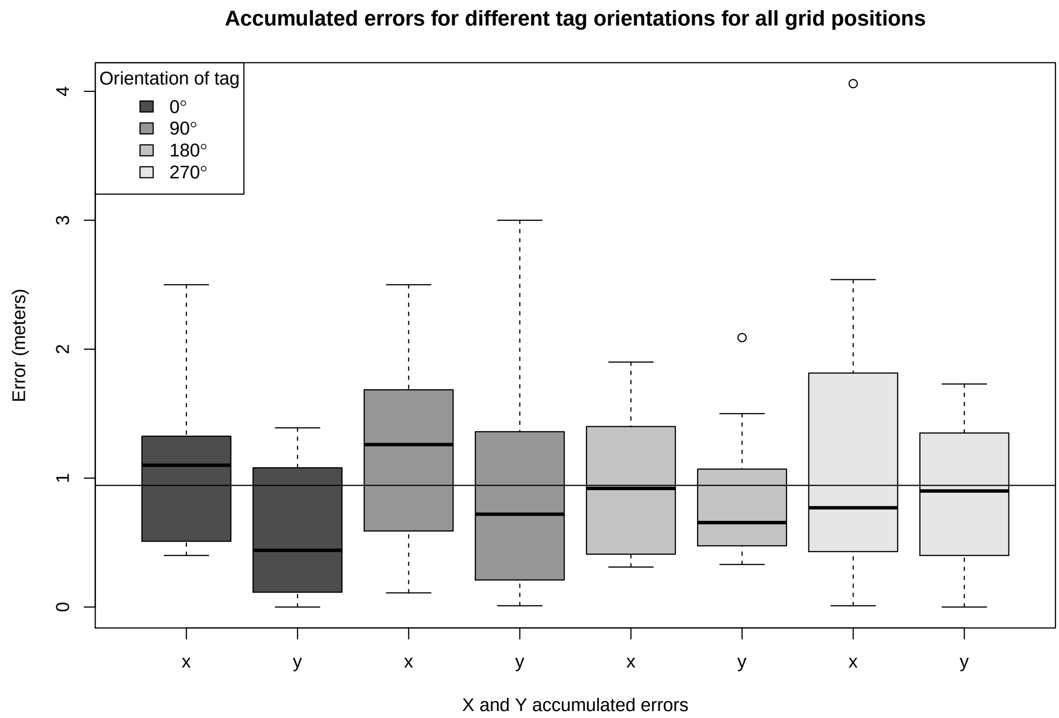


Figure 5.15: A box plot showing errors between measured and estimated locations. The boxes are organised in four groups. Each group consists of errors in the x and y axes for a particular orientation of the tag. The horizontal line across the plot is the mean of all errors regardless of the tag orientation.

Chapter 6

Discussion and Future Work

Chapter 7

Conclusion

Appendix A

Appendix

A.1 Per reader translation tables from RSSI to distance

Distance	0	1	1	2	2	3	3	4	4	5	5	6	6	7
RSSI	80	65	64	62	61	57	56	53	52	48	47	46	45	44

Table A.1: RSSI value ranges used to estimate distance when using the first reader.

Distance	0	1	1	2	2	3	3	4	4	5	5	6	6	7
RSSI	77	63	62	58	57	55	54	53	52	49	48	47	46	44

Table A.2: RSSI value ranges used to estimate distance when using the second reader.

Distance	0	1	1	2	2	3	3	4	4	5	5	6	6	7
RSSI	78	64	63	60	59	56	55	54	53	49	48	45	44	43

Table A.3: RSSI value ranges used to estimate distance when using the third reader.

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