Wisn – A Wi-Fi Indoor Positioning System

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Prof Paul Strooper
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Dear Professor Strooper,

In accordance with the requirement of the Degree of Bachelor of Engineering in the School of Information Technology and Electrical Engineering, I submit the following thesis entitled

"Wisn – A Wi-Fi Indoor Positioning System "

The thesis was performed under the supervisor of Dr Mark Schulz. I declare that the work submitted in thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at The University of Queensland or any other institution.

Yours sincerely,

Chris Berry-Porter

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Many thanks go out to Dr Mark Schulz for his help in guiding me toward some better solutions, specifically related to data communications and publish-subscribe systems.

Abstract

Detecting the presence or location of smart devices (such as phones or tablets) has a wide range of uses in today's society. This is because tracking smart devices is synonymous with tracking users since users carry these devices on them most of the time. This device and user location information can be used for a variety of purposes including being used to track traffic flow on a highway, tracking shoppers in a store to gauge certain product interest or for control of lights, power or devices in a smart home or office.

The typical method of getting the location of an object is using GPS however this does not work reliably indoors. The solution proposed by this project is to locate smart devices using wireless sniffing. This technique allows wireless devices to be detected by sensor nodes placed throughout the area where the smart devices will be found. It is a passive technique and does not require the users to install any application at all.

This document outlines the features and functionality of the proposed solution as well as the background information required to understand how the system will operate.

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1. Introduction

1.1 Project Description

One of the key benefits of using applications on mobile devices is the use of location awareness to provide a better experience for users. Location awareness allows applications to use this extra information to provide additional functionality or to automatically perform actions. Some examples where location awareness is used includes guidance and mapping applications [1], smart homes and offices [2], and tracking user activity [3], [4]. A system that tracks or otherwise locates the position of an object or device, is known as a positioning system.

There are a variety of different techniques used in positioning systems and they each have their own strengths and weaknesses. The most commonly known and used positioning system is the Global Positioning System (GPS). GPS technology has made its way into numerous devices and is the de facto solution for locating the position of an object on Earth. The major drawback of GPS however, is that it only works reliably outdoors since the signals transmitted from the satellites orbiting the Earth are easily blocked by solid obstacles such as trees and buildings. In addition to this, GPS consumes quite a lot of power. This is a significant disadvantage of mobile devices where the aim is for long battery life. These two drawbacks make GPS a poor solution for tracking objects indoors.

This is a problem because quite often, the objects that need to be tracked stay indoors. In particular, many applications require location awareness of the device they are running on or the user of the application. For humans, many spend a lot of time indoors and generally carry their mobile devices (such as a smartphones, tablets or laptops) around with them. The ideal solution then, would be to create a low cost, low power indoor positioning system that could accurately track mobile devices (and by extension their users) using pre-existing technology and infrastructure as much as possible.

1.2 Project Aim

The aim of this project was to create a modular and scalable indoor positioning system that could be used standalone or as a framework to track mobile devices. Some key requirements that have been factored into the design of this indoor positioning system are:

- Low cost
- Low power
- Maximise use of pre-existing infrastructure
- Minimise end user input
- Easy to setup and use

1.3 Project Outcomes

The indoor positioning system developed during this project supports the following features:

- Detect the area a device is located in
- Operate passively without the need for users to install an application or modify their device(s)
- Utilises an opt-in scheme for privacy
- Allow external applications access to location information
- Provide an interactive map displaying all tracked devices
- Web-based configuration of the system

1.4 Overview

This report is organised in the following manner. Section 2 describes the design decisions that went into creating the overall system architecture by covering a brief survey of indoor positioning technologies and their associated techniques for locating devices, the general overview of an IEEE 802.11 Wi-Fi positioning system, and a short overview of various data communications protocols.

Section 3 includes the required background information necessary to understand how Wi-Fi systems operate, how it is possible to calculate the distance between two radio-based devices, and how to calculate the position of an object based on fixed points and distances.

Section 4 details the system implementation broken down into the receiver, localisation and display subsystems. Section 5 displays the achieved results of the system, and Section 6 describes some future improvements that could be made to the system.

2. System Architecture

The basic system architecture for all indoor positioning systems consists of at least two main components, transmitters and receivers. Often, a third component (such as a computer or embedded system) handles the collection and processing of the location data, however this is not always the case.

A typical indoor positioning system uses receivers placed throughout the area where the devices are to be tracked to listen for signals transmitted by these devices. Based on information collected by the receivers, the location or position of the device can then be calculated based on a variety of techniques (see *2.2 Localisation Techniques* and *0*

Multilateration for more information). While this is the normal setup for an indoor positioning system, there are some cases where this is reversed. Instead, the devices that are tracked act as receivers and listen for transmitters scattered throughout the area.

2.1 Existing Approaches to Indoor Positioning

There are numerous different types of indoor positioning systems that have been developed based on different technologies, some of which are now available commercially. This section provides a brief overview of each of the major technologies used for indoor positioning systems.

2.1.1 Infrared (IR) Positioning Systems

Infrared positioning systems rely on line of sight between transmitters and receivers to transmit an infrared light signal. The distance an IR signal is effective over is roughly several metres, meaning a high density of receivers is required for tracking an object within a large open area such as a lecture theatre.

This can make IR based systems expensive to implement if more than simple room level accuracy is required, since cameras are typically used as receivers. Additionally, all the receivers must be connected to a central point where the data is processed. While this is the case for most sensor networks, if there is a high density of receivers, then the networking costs can become significant. In addition to this, florescent light and sunlight interfere with IR sensing unless some kind of optical, electronic or software filter is included at each receiver which may further increase costs.

Despite these limitations, infrared positioning systems are used in a variety of applications. They are some of the most accurate positioning systems available for a small area when implemented correctly. One of the most common applications for accurate IR positioning systems is motion capture. This is the technique of digitising the movements of objects or people. Some active infrared motion capture systems are available where sub-millimetre accuracy is possible [5].

More general solutions such as the Active Badge system, designed and developed by AT&T Cambridge, offers IR tracking for much larger areas, such as within a building. The system uses badges which emit a unique IR signature periodically. A number of receivers listen for these signatures and can detect where a badge is located. While the Active Badge system increases the coverage area for tracking (compared to other IR based systems), the accuracy has been decreased substantially, offering only room level accuracy and requires an IR receiver to be present in every room [6].

2.1.2 Ultrasonic Positioning Systems

Ultrasonic positioning systems make use of high frequency sound waves above the human hearing range. This allows for operation using sound waves without disturbing humans, although it can still upset other animals such as dogs [7]. An important difference between ultrasonic based systems and other radio based systems is that the transmitter ID is not transmitted via ultrasound. This means some alternate means must be implemented so that receivers can know which transmitter is transmitting.

An example of a system that uses ultrasound to locate devices, is AT&T Cambridge's BAT location system. BAT is AT&T Cambridge's second attempt at implementing a wireless, low-cost and low-power indoor positioning system after first implementing the Active Badge system (see *2.1.1 Infrared (IR) Positioning Systems*). BAT consists of multiple ultrasonic receivers positioned in a square grid array with a distance of 1.2m between receivers. All receivers are connected by a high speed serial network in a daisy-chain fashion terminated with a DSP calculation board [8]. This DSP board performs all the processing necessary to find the position where the signal originated from.

The transmitters in this system are known as "bats" and are relatively small devices that emit an ultrasonic signal when they receive a message via radio. A central controller manages when bats should emit a signal using radio communications. The central controller is also responsible for collecting position data from the DSP board(s) and forwarding it on to external applications.

While the BAT system boasts impressive accuracy of within 3 cm and can track multiple "bats" in real-time [8], it also has some major downsides too. The biggest problem with this system is the cost associated with installing it. The system does not use any pre-existing infrastructure and relies on a high density of receivers in order to perform well. This causes the cost of the system to increase significantly due to the cost of the receivers themselves, as well as the cost associated with installing a private serial network just for the receivers to use.

An alternative ultrasonic positioning system with a different take on the implementation has been developed by MIT. Called Cricket, this system is different because instead of using many receivers to track a transmitter, many transmitters are used to allow receivers to find their own position [9].

The Cricket system is decentralised and does not have a central controller like the BAT system. This means that transmitters need to not only produce an ultrasonic signal, they also emit an RF signal. This is so that receivers know which transmitter the ultrasonic signal came from. Receivers use identical hardware to the transmitters, but instead must be connected via serial to a host device such as a laptop or PDA.

There are a number of benefits to this setup compared to the BAT system. One of the major benefits is that because the receivers do all the position calculations, there is no need for a central control unit or a requirement to connect all transmitters together. This means that although the system does not use pre-existing infrastructure, it is much less costly to setup since only transmitters are required. In addition to this, the system is much more flexible since receivers and transmitters use the same hardware and can be used for either role. The positional accuracy of the system is within 10 cm and it is also able to give a heading accurate to within 3° [9].

The Cricket system does however, suffer from a few flaws. One of which is that the transmitter and receiver units run off a battery. Since both ultrasonic and RF signals are being transmitted frequently, they tend to use more power and can result in the need for frequent battery charging.

While ultrasonic signals can travel further than IR signals, they are still limited to within a room since solid objects and obstacles block the signal. Ultrasonic positioning systems also suffer from reflections and other interference such as multipath fading which considerably decreases their effectiveness in situations where the path between transmitter and receiver is obstructed.

2.1.3 Ultra wideband (UWB) Positioning Systems

One of the more recent methods used for indoor positioning, ultra wideband positioning systems operate similarly to other radio frequency based positioning systems. A UWB signal is a radio signal comprised of digital pulses and having a bandwidth of greater than 500

MHz. While the allowed frequency range for ultra wideband differs from country to country, the UWB frequency range is typically anything from 2 GHz and up for consumer use, albeit with some limits to transmit power [10], [11]. These characteristics provide some benefits for UWB signals compared to other narrowband radio signals.

Firstly, because UWB has such a large bandwidth, it is more resistant to interference caused by reflections and multipath fading, which significantly helps for indoor usage. It is also better at penetration through walls and other indoor obstacles because its broad bandwidth makes it difficult to block the entire frequency range of the signal.

In addition to this, because high frequencies can be used, the pulse length used for UWB can be extremely short [12]. This makes it possible to filter direct signals from reflections, because reflections will be received after the direct signal and there will not be any overlap due to the short pulse length.

Based on this technology, Ubisense has developed a commercial indoor positioning system. The system consists of UBW receivers placed throughout the area where devices will be tracked, and transmitters called tags. Ubisense typically deploys at least four receivers per 400 m^2 [13]. These receivers are then connected via Ethernet to Ubisense's software platform which handles processing and display of positional data.

Ubisense states that their system is capable of accuracy of up to 15 cm which, considering the very low density of receivers, is an excellent accuracy to achieve. In addition to this, Ubisense is able to take advantage of existing network infrastructure to connect their receivers to which helps make the installation less costly.

There are some downsides to UBW systems though. Many systems that implement receivers with antenna arrays, such as Ubisense, can be expensive. This is due to the cost of multiple antennas and the hardware required to be able to individually receive from each antenna. For example, Ubisense offers a research package, which consists of four receivers and five transmitter tags, with a cost of over $15,000 [13].

2.1.4 Bluetooth Positioning Systems

Bluetooth is a low-power communications technology designed for short distance data exchange using radio signals in the 2.4 GHz band. It is a common technology found in most of today's modern mobile devices, so it makes perfect sense to try and leverage Bluetooth for indoor positioning systems.

While there have been a few attempts at creating an indoor positioning system using Bluetooth, Apple has been responsible for standardising the most well-known system called iBeacons. iBeacons are not solely designed for indoor positioning systems, but rather for context-aware applications such as advertising [14].

An iBeacon is a small, generally battery powered, Bluetooth enabled device that transmits messages to other Bluetooth devices. Using the iBeacon API it is possible to get three proximity levels of distance between the beacon itself and a Bluetooth device. These levels are immediate (as close as a few centimetres), near (within a couple of metres) and far (up to 10 metres away) [15]. With this sort of granularity over distance measurements, it makes it difficult to produce an indoor positioning system with better than room level or simple proximity accuracy.

Aside from Apple's implementation, other Bluetooth focused positioning systems such as Topaz have been developed. Topaz works similarly to other radio based positioning systems by using many receivers to listen for devices, although it does also incorporate IR technology to increase accuracy. Topaz is capable of reaching an accuracy of 2 m [16]. The reason this is not as accurate as some of the other types of positioning system already mentioned is due to Bluetooth being strongly affected by reflections, multipath fading and other signal interference when indoors like most other radio based systems.

2.1.5 IEEE 802.11 Wi-Fi Positioning Systems

The IEEE 802.11 Wi-Fi wireless networking standard is one of the most popular and common wireless networking technologies to be created. Wi-Fi is a data communications protocol that uses the 2.4 or 5 GHz radio bands in order to connect many wireless devices at speeds of up to 1 Gbps [17]. Due to its popularity, almost all new mobile or personal electronic devices include some version of Wi-Fi functionality.

One of the major advantages of Wi-Fi based positioning systems is that they can take advantage of the prolific infrastructure already in use. Wi-Fi is primarily used for functionality other than indoor positioning systems, which means that there are always Wi-Fi signals being sent, while devices are being used. This gives Wi-Fi positioning systems the option to locate devices passively by just using receivers, without needing to provide their own transmitters. This can even be taken a step further by using the access points that all wireless devices connect to as receivers. In addition to this, users do not need to install any additional applications or make any changes to their devices in order for them to work with a passive Wi-Fi positioning system.

Wi-Fi, like most other radio based systems, suffers from reflections, multipath fading and other signal interference when used indoors. In addition to this, there is huge variability in the transmit power of Wi-Fi devices due to antenna and radio differences. Some devices even automatically adjust the transmit power themselves in order to save battery life. This can make calibration for distance calculations challenging. This typically limits most Wi-Fi based positioning systems to accuracies of roughly 2-3 m when used in relatively unobstructed environments [13].

2.1.6 Summary

As can be seen, there are numerous different technologies and systems available for implementing an indoor positioning system. Each one has its own advantages and disadvantages as listed below in Table 1 below.

Table 1: Summary of Indoor Positioning System Technologies

System Type	Advantages	Disadvantages	Typical Accuracy
Infrared	• Highly accurate • Small, cheap transmitters	• Line of sight • Expensive receivers	1 – 5 mm or Room level accuracy
Ultrasonic	• Accurate •	• High density • Sync required	1 – 10 cm
Ultra wideband	• Low density • Good indoor penetration	• Expensive •	10 – 15 cm
Bluetooth	• Bluetooth common in devices • Low power	• Noisy • Short range	2 – 3 m
IEEE 802.11 Wi-Fi	• Existing infrastructure • Low density	• Noisy • Many channels	2 – 3 m

Sadly, none of these systems are perfect, but in order to design an indoor positioning system that satisfies the goals set out in *0*

Project Aim, Wi-Fi was selected as the best technology to use. This is because using Wi-Fi allows for heavy reuse of pre-existing infrastructure, and a passive solution can be implemented. This saves on the cost of the system and means less installation is required. It also saves on power since by itself, the system does not transmit anything, nor does it cause devices to transmit additional data.

2.2 Localisation Techniques

In order to find the position of an object or device, each of the technologies listed in Section 2.1 use one or more different techniques. This section briefly describes how each one works, and which is applicable for each technology.

2.2.1 Time of Arrival (ToA)

Time of Arrival is one of the more commonly used methods for calculating the distance between a transmitter and receiver. In a ToA system, there is a common clock shared between transmitters and receivers. This is done so that both transmitters and receivers are synchronised, so that there is no difference in delay when taking a measurement.

ToA systems measure the time taken for a signal to travel from a transmitter to a receiver. The distance between the two can be found by using the simple formula:

$$distance = velocity \times time$$

The velocity will depend on what sort of signal is transmitted (such as radio or sound) and through what medium it will travel (such as air or water) but this will stay constant. Distances calculated using this method can then be used in the multilateration process in order to find the position of the transmitter or receiver (see *0*

Multilateration for more information). Indoor positioning systems based on ultrasound, UWB or IR may use ToA as part of their localisation process.

2.2.2 Received Signal Strength Indicator (RSSI)

Received Signal Strength is another method for calculating the distance between a transmitter and receiver. RSSI, as the name implies, measures the signal strength of received signals. Using one of the many RSSI distance models (see *3.2 RSSI Distance Models* for more information), a distance can be calculated using the signal strength. The formula used to calculate the distance varies depending on the exact model used, and on environmental factors; since signal strength can change drastically when multipathing and other interference from obstructions is present.

Distances calculated using this method can then be used in the multilateration process in order to find the position of the transmitter or receiver (see *0*

Multilateration for more information). Systems that can use RSSI are generally radio-based systems such as Wi-Fi, Bluetooth or UWB.

2.2.3 Angle of Arrival (AoA)

Angle of Arrival is a slightly different method of determining position compared to ToA and RSSI. Instead of measuring the distance between the transmitter and receiver, AoA measures the angle at which the signal was received. By measuring two of these angles and knowing the distance between the two transmitters, the process of triangulation can be used to find the position of the receiver. Indoor positioning systems based on ultrasound are able to implement AoA as part of their localisation process.

2.2.4 Summary

Listed below in Table 2 is a list of which indoor positioning system technologies support the different localisation methods. Note however, that it is possible to implement some of these localisation methods for other technologies, however it typically requires lower level access to the hardware or custom solutions. There are also other additional localisation techniques available for some of these technologies but this falls outside the scope of this project.

Table 2: Summary of Localisation Methods

Localisation Method	Technologies
Time of Arrival (ToA)	IR, Ultrasound and UWB
Received Signal Strength Indicator (RSSI)	Wi-Fi, Bluetooth and UWB
Angle of Arrival (AoA)	Ultrasound

As can be seen above, RSSI is the localisation method of choice for a Wi-Fi based positioning system. As such, RSSI was chosen as the localisation method of choice.

2.3 General Wireless Localisation System Overview

As with most other radio-based indoor positioning systems, Wi-Fi based positioning systems typically use many receivers placed throughout the area where devices will be tracked. In this case, the objects are Wi-Fi devices such as smartphones, tablets and laptops. These Wi-Fi devices act as the transmitters in the system, and will be tracked based on the RSSI of their transmitted signals.

The receivers in the system are responsible for listening for all Wi-Fi signals transmitted. The receivers in the system could be the access points that wireless devices connect to, or separate receivers might also be used. This depends upon the types of access points available and whether they will support being used as part of an indoor positioning system.

As receivers gather data on Wi-Fi signals being transmitted, the data is typically collated and processed by a central device which is then responsible for using the data to calculate the position of a device. This requires that each receiver is able to communicate with the central processing device in some way.

For a Wi-Fi indoor positioning system, there are two simple options that take advantage of pre-existing infrastructure. The first is to use Wi-Fi itself to transmit the data to the central device. The alternative option is that because all access points (which may be used as receivers) must be connected via Ethernet in order to connect devices wireless to a network, the data can simply be sent over the wired network using Ethernet. The second method is typically favoured for large systems since it reduces the amount of Wi-Fi traffic generated by the system itself.

2.4 Data Communications

As described in *2.3 General Wireless Localisation System Overview*, each receiver in the indoor positioning system must communicate with the central processing device in order to send it collected data. While the physical hardware used can be either Ethernet or Wi-Fi, there are a number of different software protocol choices available that greatly affect the way in which communications occur. This section provides a short overview of some different communications protocols.

2.4.1 Point to Point Communications

The most commonly used communications system, point to point communications or messaging, allows two separate entities to communicate. The most common architecture using a point to point communications system is the client-server model.

This model uses one entity as a server, which is responsible for waiting and servicing all clients that connect to it. A server is capable of serving multiple clients at once but of course the server will reach a limit where there will not be enough resources to deal with additional clients. While clients can communicate directly with the server, client to client communication can only be achieved by communicating through the server as a proxy.

While this model is very simple, there are a couple of drawbacks. One such disadvantage is that client-server systems are highly coupled. This means that clients will not function without an active server and vice versa. Another disadvantage is that broadcasting data to multiple clients in a point to point system requires individually sending the same message to each client, which costs additional resources.

2.4.2 Publish-Subscribe Communications

The publish-subscribe communications system is a very different one compared to point to point systems. A publish-subscribe system consists of publishers, which are responsible for producing content or messages, and subscribers, which are responsible for consuming the content or messages.

While this may sound similar to the client-server roles, the major difference here is that in a publish-subscribe system, publishers and subscribers are ignorant of each other. That is to say, a publisher does not know about how many subscribers there are, if any at all. This allows publishers and subscribers to be decoupled and work independently.

The system works by implementing a central broker. The broker is the entity that all publishers and subscribers connect and communicate with. When publishers publish new content to the broker, it is published to a “topic”. This topic acts as the identifier for the content and allows any subscriber access to the content. Subscribers subscribe to these topics so that they can receive any content published to the topic, regardless of which publisher sent it. Publishers can publisher to multiple topics and subscribers can subscribe to multiple topics too.

This system brings many benefits including allowing publishers and subscribes to publish or subscribe without relying on the other. In addition to this, the system can be used to great effect to allow for all data to be sent via one connection. This is because a publisher can broadcast to as many subscribers subscribed to a topic with a single message. Subscribers are also able to collect data from many different subscribers and topics via a single connection to the broker.

The major downside to this system however, is that since the content producer is decoupled from the content consumer, both of them must stick to using a known data format. If a publisher was to change its data format, the subscribers would very likely not use the data received correctly unless they too are updated to use the new format.

There are a range of different protocols available implementing the publish-subscribe architecture all with different goals. A short summary of the most common protocols are listed below.

2.4.2.1 Advanced Message Queuing Protocol (AMQP)

AMQP is a very large, complex and propriety messaging protocol supporting publish-subscribe architecture. It is designed for large scale enterprise systems that focus on reliability, security and performance [18]. This makes AMQP a poor choice for a relatively small system where being lightweight is a key factor.

2.4.2.2 Simple Text Orientated Message Protocol (STOMP)

STOMP is a communications protocol that implements publish-subscribe architecture in a format that is very similar to the HyperText Transfer Protocol (HTTP), more commonly known as the protocol that delivers most websites today. STOMP is designed this way in order to allow clients and servers to be language agnostic, so that different versions of clients and servers will work together regardless of the platform they run on [19].

2.4.2.3 Extensible Messaging and Presence Protocol (XMPP)

XMPP is an Extensible Markup Language (XML) based communications protocol. One of the many implemented features within XMPP is publish-subscribe architecture [20]. XMPP is very similar to AMQP and offers a range of different features, many of which are not required for small, lightweight systems.

2.4.2.4 Message Queue Telemetry Transport (MQTT)

MQTT is another communications system that implements publish-subscribe architecture. MQTT is a lightweight messaging protocol designed for “constrained devices and low-bandwidth, high-latency or unreliable networks” [21]. The driving force behind MQTT is to minimise network bandwidth and device requirements while still attempting to ensure reliability [21]. This makes MQTT a very suitable choice as a communications protocol for embedded systems and sensor networks.

2.4.3 Summary

As already seen, point to point messaging systems do not offer the flexibility that publish-subscribe systems do. This is particularly important for sensor networks and indoor positioning systems where receivers may not always be connected to the central processing device via reliable means. Due to the decoupled nature of publish-subscribe systems, this problem can be easily worked around.

In terms of which publish-subscribe protocol suits an indoor positioning system best out of the four briefly described here, it is clear that MQTT with its focus on being lightweight in both network bandwidth and device resources is the best choice.

3. Background

3.1 IEEE 802.11 Wireless Networking (Wi-Fi)

IEEE's 802.11 wireless networking standard (more commonly known as Wi-Fi) is the most common wireless networking system used today. It has been updated numerous times since it was first developed in 1997 [22] in order to add more bandwidth and features. The most widespread variants in use today are 802.11g and 802.11n. An important note about the 802.11 specification is that since it is using radio signals to communicate, it is half-duplex, i.e. only a single device can transmit at a time.

The 802.11 specification is huge and includes specifications for a diverse range of different wireless setups. For the purpose of a passive Wi-Fi indoor positioning system that takes advantage of pre-existing infrastructure, only the relevant information for the most commonly used 802.11 setup will be described in this section.

3.1.1 802.11 Hardware

Within the 802.11 specification, two main pieces of hardware are essential. One of these pieces of hardware are wireless devices (such as smartphones, tablets or laptops) that are to be connected wirelessly together, as well as to a broader network. The 802.11 specification refers these devices as stations (STA). Despite the naming convention, these are not base stations that other devices connect to.

The other essential piece of hardware is the device that all stations connect to, an access point (AP). Access points are responsible for connecting stations to the rest of the network and to other stations connected wirelessly. The rest of the network is typically referred to as the distribution system (DS) [22].

3.1.2 802.11 Concepts

3.1.2.1 Channels

The 802.11 wireless specification mainly uses two different radio frequency bands for transmission, 2.4 and 5 GHz. The 5 GHz band is not as commonly used as 2.4 GHz, and the range of 5 GHz signals is far shorter than 2.4 GHz indoors, so 2.4 GHz will be the main focus for indoor positioning systems [23].

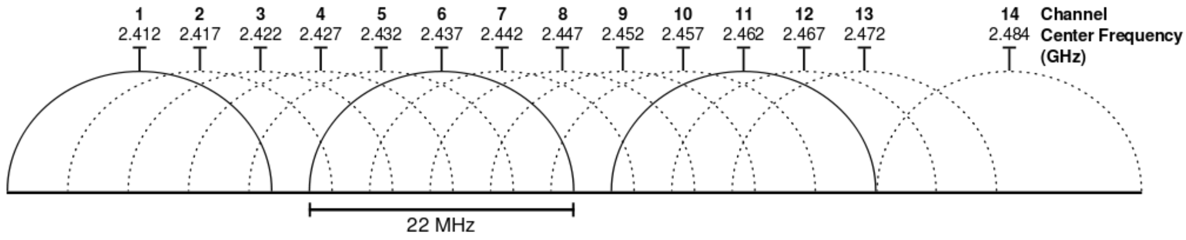

Figure 1: 2.4 GHz Wi-Fi Channels [24]

The 2.4 GHz band is split up into 14 separate channels as seen in Figure 1 above. Many of these channels overlap, however the purpose of having different channels is to allow for multiple wireless systems to be operational in the same area without interfering with each other. This means that stations connected to different channels will not be able to communicate with each other. Stations connected to the same access point are not affected by this since each access point can only offer a single channel to connect to at a time.

3.1.2.2 Packets

The 802.11 specification describes a system of radio transmitters and receivers that are able to transfer data wirelessly using radio signals. In order to transfer this data, 802.11 describes a concept called packets. Packets are basically short chunks of data plus some additional information about the packet itself, called a header. This is done to break up very long streams of data so that packets from multiple devices can be interleaved, as well as to decrease retransmission times if a packet arrives corrupt. The important part of a packet for Wi-Fi indoor positioning systems is the header that is included with each packet.

3.1.2.3 Media Access Control (MAC)

It is necessary for all networking devices to identify themselves by some means. This is done by using a MAC address. A MAC address is a unique identifier used by many IEEE 802 network specifications. MAC addresses are essentially a 48 bit number. They are often represented in human readable form as six groups of two hexadecimal digits, separated by either hyphens or colons, such as 00:15:3C:73:5F:C1.

A wireless module is given a MAC address during manufacturing and under normal circumstances, will always stay the same. Since a MAC address provides a unique way to track where a packet originated from, it is always included as part of the header added to each packet transmitted. Wi-Fi indoor positioning systems use these MAC addresses in order to track wireless devices.

3.1.3 802.11 Header Formats

In order for a Wi-Fi indoor positioning system to function, it is necessary to extract some key pieces of information out of packet headers. Figure 2 below, shows the format of the MAC header prepended to each data packet before being transmitted.

Octets: 2	2	6	6	6	2	6	2	4	0–7951	4
Frame Control	Duration /ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	QoS Control	HT Control	Frame Body	FCS

MAC Header

Figure 2: 802.11 MAC Header

The 802.11 specification states that for the majority of packets, the *Address 2* field will contain the MAC address of the station that transmitted the packet [22]. There are a few exceptions to this rule, however they can be filtered out by reading the data contained in the *Frame Control* field shown below in Figure 3.

	B0 B1	B2 B3	B4 B7	B8	B9	B10	B11	B12	B13	B14	B15
	Protocol Version	Type	Subtype	To DS	Fro m DS	More Frag- ments	Re- try	Power Manage- ment	More Data	Protect- ed Frame	Or- der
Bits:	2	2	4	1	1	1	1	1	1	1	1

Figure 3: 802.11 Frame Control Field

Within the *Frame Control* field, the bits that make up the *type*, *subtype*, *to DS*, and *from DS* sections, can be read to find the purpose of the packet. Both the *type* and *subtype* bits detail what sort of packet this is, and whether or not this packet contains useful information about a wireless device for tracking purposes or not. The *to DS* and *from DS* bits describe whether the packet is being sent from a station to an access point, or whether an access point is sending the packet to a station. This is important because a Wi-Fi positioning system is only interested in the packets sent by stations, not those sent by access points.

3.1.4 Radiotap Header

In addition to the 802.11 MAC header that is prepended to every packet sent by a station, receivers (both access points and stations) also prepend their own header called the Radiotap header.

```
Radiotap Header v0, Length 26
  Header revision: 0
  Header pad: 0
  Header length: 26
⊟ Present flags
    .... .... .... .... .... .... .... ...1 = TSFT: True
    .... .... .... .... .... .... .... ..1. = Flags: True
    .... .... .... .... .... .... .... .1.. = Rate: True
    .... .... .... .... .... .... .... 1... = Channel: True
    .... .... .... .... .... .... ...0 .... = FHSS: False
    .... .... .... .... .... .... ..1. .... = dBm Antenna Signal: True
    .... .... .... .... .... .... .1.. .... = dBm Antenna Noise: True
    .... .... .... .... .... .... 0... .... = Lock Quality: False
    .... .... .... .... .... ...0 .... .... = TX Attenuation: False
    .... .... .... .... .... ..0. .... .... = dB TX Attenuation: False
    .... .... .... .... .... .0.. .... .... = dBm TX Power: False
    .... .... .... .... .... 1... .... .... = Antenna: True
    .... .... .... .... ...1 .... .... .... = dB Antenna Signal: True
    .... .... .... .... ..0. .... .... .... = dB Antenna Noise: False
    .... .... .... .... .0.. .... .... .... = RX flags: False
    .... .... .... .0.. .... .... .... .... = Channel+: False
    .... .... .... 0... .... .... .... .... = HT information: False
    .... .... ...0 .... .... .... .... .... = A-MPDU Status: False
    .... .... ..0. .... .... .... .... .... = VHT information: False
    ...0 0000 00.. .... .... .... .... .... = Reserved: 0x00000000
    ..0. .... .... .... .... .... .... .... = Radiotap NS next: False
    .0.. .... .... .... .... .... .... .... = Vendor NS next: False
    0... .... .... .... .... .... .... .... = Ext: False
  MAC timestamp: 110317703
```

Figure 4: Radiotap header [25]

As can be seen in Figure 4 above, the Radiotap header contains some important physical information in regards to the radio signature of the received packet. This includes the channel the packet was transmitted on and, most importantly, the RSSI of the packet in dBm.

3.2 RSSI Distance Models

In order to be able to calculate the position of a wireless device, it is necessary to first calculate the distance between the device and the receivers. This is done by using an RSSI distance model. There are numerous different models available, some of which are based on statistical models in an effort to cope with noisy RSSI measurements, however this falls outside the scope of this project. The two most commonly used models are summarised below.

3.2.1 Free Space Path Loss Model (FSPL)

The FSPL model is based upon electromagnetic wave theory which states that the amplitude of an electromagnetic wave is inversely proportionally to the square of the distance between the transmitter and receiver, as well as the square of the frequency of the wave. The FSPL equation is:

$$FSPL\ (dB) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

Where:

d is the distance in metres between the transmitter and receiver.
f is the frequency of the wave in Hertz.
c is the speed of light in a vacuum in m/s.

Since the frequency and speed of light stay constant, this equation can then be rearranged to find the distance given the RSSI path loss instead. The main problem with this model is that it is designed for use in a completely ideal environment with no interference affecting transmissions. This is of course not the case when transmitting indoors, however this model is the main model that most other RSSI distance models use.

3.2.2 Log-distance Path Loss Model

The Log-distance path loss model (LDPL) takes the FSPL model and adds an attenuation factor in order to simulate interference. The Log-distance equation is:

$$LDPL\ (dB) = FSPL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right)$$

Where:

d is the distance in metres between the transmitter and receiver.
d_0 is the reference distance in metres.
n is the path loss exponent.

The reference distance is typically chosen to be just within the far-field of the transmitter and receiver. This is because the FSPL model (which the LDPL model relies upon) will only hold for distances in the far-field, however the reference distance affects the smallest distance measureable, thus it is best to keep it as small as possible. Since the reference distance is kept constant, the path loss at the reference distance can be calculated once and then kept constant.

The path loss exponent introduces an attenuation factor that helps to simulate interference when transmitting indoors. Table 3 below lists some common path loss exponents for different environments. To reach the best accuracy, calibration must be performed with the system in the actual usage environment in order to determine the best value for the path loss exponent.

Table 3: Path Loss Exponents for different environments [26]

Environment	Path Loss Exponent (n)
Free Space	2
Urban area cellular radio	2.7 – 3.5
Inside a building – line of sight	1.6 – 1.8
Obstructed in a building	4 – 6
Obstructed in a factory	2 – 3

The path loss at the reference distance and path loss exponent stay constant once calculated, this means this equation can be rearranged to find the distance given the RSSI path loss. While this model is not perfect at calculating the distance based on RSSI, it gives a much closer estimate to the actual distance for indoor environments compared to the FSPL model.

3.3 Multilateration

Multilateration is the process of determining the position of an object given the absolute positions of three points and the distance between those points and the object. When three distances are known, this is known as trilateration, however for situations where more than three distances are known, the process is called multilateration.

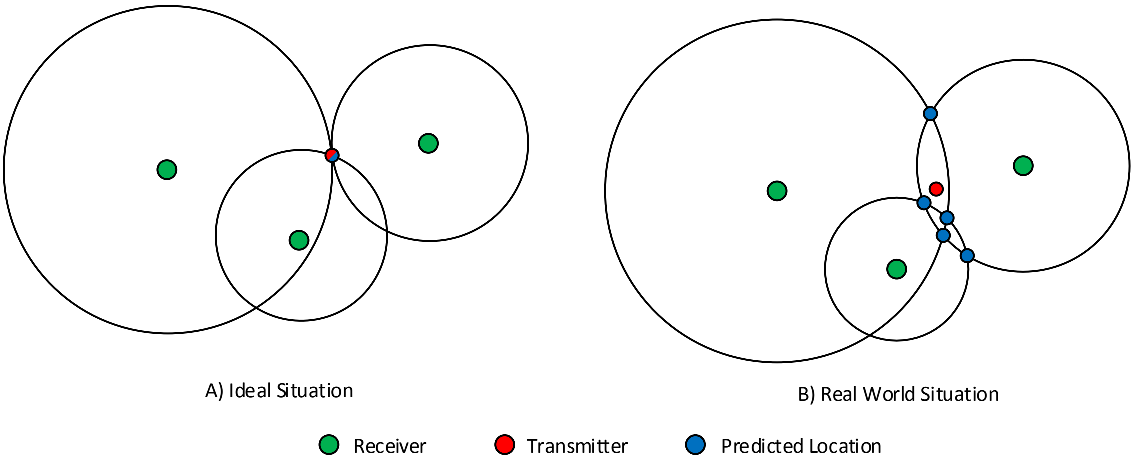

Figure 5: Multilateration Scenarios

As can be seen above in Figure 5, a visual description of how multilateration works is that it plots a circle centred on a receiver with a radius equal to the distance between the transmitter and receiver. The transmitter therefore lies somewhere on this circle. This is then repeated for each of the other receivers.

The end result is many circles that overlap. Ideally, all circles will intersect at a single point where the transmitter is actually located (as shown in Figure 5A), however it is common for the circles to not intersect at a single point, or not at all due to many factors such as multipath fading, reflections and other interference that affects the RSSI distance calculations. In these situations (as shown in Figure 5B) an averaging and interpolation algorithm needs to be applied in order to better approximate the actual position of the transmitter. A commonly used method to reduce the approximation error is to run some type of regression after multilateration.

4. System Implementation

The Wi-Fi indoor positioning system described in this section is a result of the requirements outlined in *0*

Project Aim and from comparing a range of different methods for various components used in indoor positioning systems. The system has been named *Wisn* because the system operates using wireless sniffing. A system overview of Wisn can be seen in Figure 6 below. Wisn has been developed to include the following features:

- Passive Wi-Fi based indoor positioning system
- RSSI ranging and multilateration used for position calculations
- MQTT used for all data communications
- Central server used to collect data and process position information
- Separate receivers used
- Capable of tracking multiple Wi-Fi devices at once

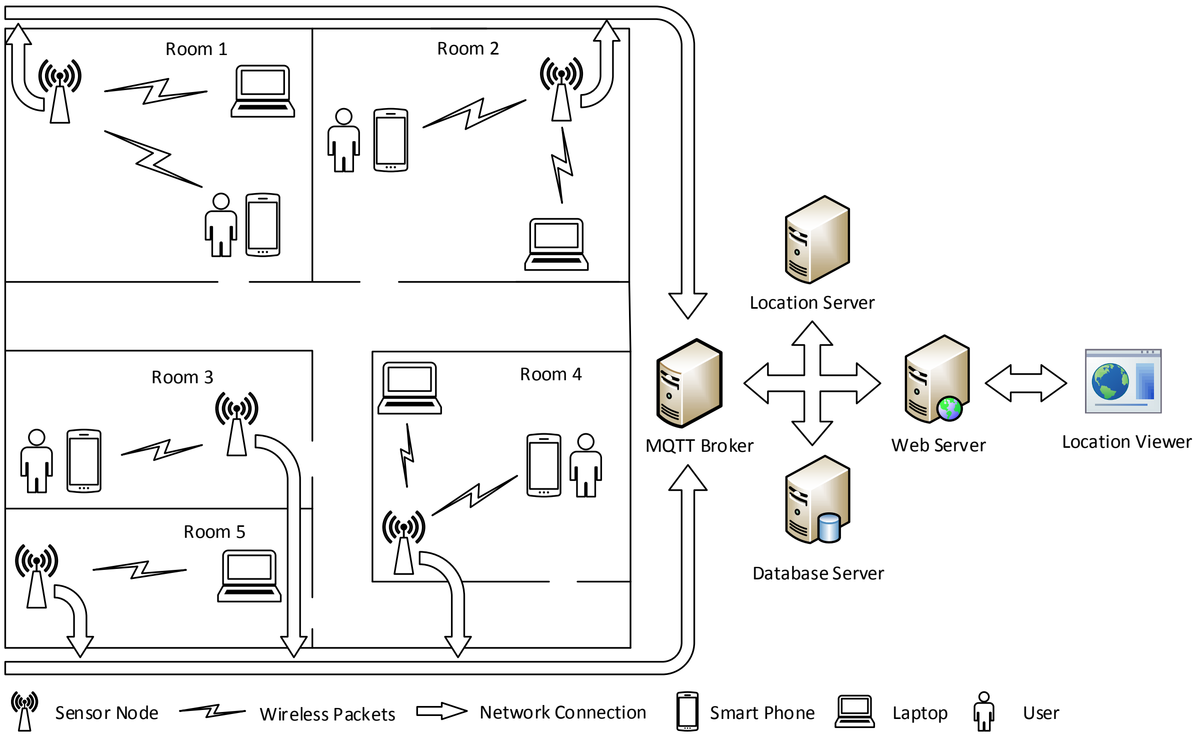

Figure 6: Wisn System Overview

4.1 Receiver Subsystem

4.1.1 Receiver Hardware

External receivers were used for the development of this Wi-Fi indoor positioning system. This was done because using external receivers allowed for much higher specification hardware to be used, compared to that typically used in Wi-Fi routers. Another advantage to this was the flexibility to setup a custom environment using Debian Linux which allowed for a more complete development environment to be used. Receivers were connected via Ethernet to the central server. This was done so that receivers could maximise the use of their Wi-Fi adapters for capturing packets rather than spend time transmitting as well.

The receivers in the system were composed of two pieces of hardware, a low power single-board computer and a USB Wi-Fi adapter. Several different types of single-board computer were used including a Raspberry Pi, a BeagleBone and a BeagleBone Black. For the tasks that the receiver performs, the system requirements are fairly low, so low power processing units such as those listed above are more than capable.

For the Wi-Fi adapter, Alfa AWUS036H adapters were used. These Wi-Fi adapters only support 802.11b/g, however the receive sensitivity (up to -96 dBm [27]) of these adapters is excellent compared to some other common wireless adapters [28]. This allows them to receive more distant transmissions, although it does mean that some 802.11n traffic is not received. This was not deemed to be a significant disadvantage though, since many 802.11 packets transmitted are not at 802.11n speeds. This includes control or management packets that all devices, regardless of which specification they implement, must be able to receive.

4.1.2 Receiver Software

The software that runs on the receivers was developed specifically for this project and primarily makes use of the low-level network packet capture library, pcap. Using pcap, it is possible to passively listen for transmitted Wi-Fi packets and then process them. The receiver software performs the following tasks:

- Capturing Wi-Fi packets using pcap
- Filtering out access point and other non-useful packets based on the 802.11 header
- Reading RSSI values from the Radiotap header

- Averaging and storing RSSI values per device
- Publishing averaged RSSI values via MQTT

In addition to this functionality, one other feature implemented is a simple channel analyser. The channel analyser runs during the first five minutes of every hour while the receiver is running. During this time, the receiver cycles through each of the fourteen Wi-Fi channels. As this is happening, a tally of how many packets received on each channel is stored. At the end of the five minute period, the receiver will calculate how much time to spend listening on each channel based on the proportion of packets received during the analysing stage. An example of the results of this process is shown below in Figure 7.

```
Total packets: 85144
Channel 1 received 80896 packets, allocating 3420 seconds.
Channel 2 received 40 packets, allocating 1 seconds.
Channel 3 received 480 packets, allocating 20 seconds.
Channel 4 received 2 packets, allocating 0 seconds.
Channel 5 received 1246 packets, allocating 52 seconds.
Channel 6 received 36 packets, allocating 1 seconds.
Channel 7 received 18 packets, allocating 0 seconds.
Channel 8 received 11 packets, allocating 0 seconds.
Channel 9 received 17 packets, allocating 0 seconds.
Channel 10 received 5 packets, allocating 0 seconds.
Channel 11 received 106 packets, allocating 4 seconds.
Channel 12 received 17 packets, allocating 0 seconds.
Channel 13 received 2231 packets, allocating 94 seconds.
Channel 14 received 39 packets, allocating 1 seconds.
Changing channel to 1
```

Figure 7: Channel Analyser Results

4.2 Localisation Subsystem

The localisation subsystem consists of the central server, an MQTT broker and a MongoDB database. The MQTT broker is the centre point to which all receivers and the central server connect to. All data communicated throughout the receivers and central server passes through the MQTT broker. The MQTT broker and MongoDB database are not required to run on the same physical device as the central server.

There are no specific hardware requirements for what sort of device the server should run on. As long as the device can run Linux and has a network connection, it is likely to be capable of running the central server software. The central server itself has been specifically developed for this project and performs the following tasks:

- Filter all incoming data by device using database of registered devices
- Keep track of receiver positions in database
- Keep track of calibration data in database
- Calculate and average device positions using RSSI ranging and multilateration
- Publish averaged device position data via MQTT
- Update last know device position in database

Keeping track of receiver positions and calibration data is very important for the central server since both greatly affect the accuracy of the calculated positions. The calibration data is used to convert between metres and the internal co-ordinate system used by the display subsystem.

The RSSI ranging model used is the same as that described in *3.2.2 Log-distance Path Loss Model*. Positions are calculated from this these distances and the receiver positions using multilateration. A least squares regression is run after multilateration in order to minimise the position error. Finally, the position data is averaged and allows for a radius around the position to be calculated based on the spread of the data. This radius is the area that the Wi-Fi device is most likely to be inside of.

4.3 Display Subsystem

The display subsystem consists of a Node.js webserver running a customised Google Maps web application designed for configuring the system and viewing positions of devices. A web-based approach to the display subsystem was taken due to the platform agnostic nature of web applications, meaning positions of devices can be displayed on any system that is capable of running a web browser. The display subsystem is split up into three parts, the opt-in component, the configuration component, and the display component.

4.3.1 Opt-In Component

The opt-in component is a very simple HTML form which allows users to register their devices with the system by providing a name for the device as well as the MAC address. The name does not have to be unique and is only used for display purposes. This data is then stored in the MongoDB database. Conversely, there is also an opt-out component to allow users to stop the system tracking their already registered devices. The MAC address is the only piece of information required to opt-out of the system.

4.3.2 Configuration Component

The configuration component is designed to be a simple and easy way to perform all system configuration and management. The configuration page consists of a Google Map showing the map of the area where device tracking will occur. The term node, is used within the Wisn system to refer to the virtual representations of the real hardware receivers. This is done so that the two can be differentiated. Nodes are used to mark the position of receivers on the map which the central server needs in order to use multilateration. By right-clicking the configuration page, as shown in Figure 8 below, nodes can be added, deleted or dragged around the map to match the position that their matching receiver occupies in the real world. Node markers appear as a blue colour.

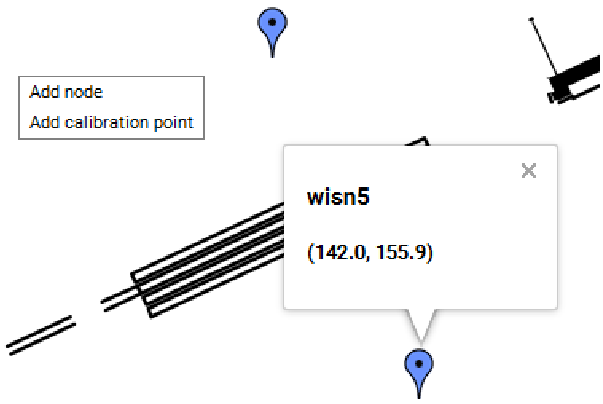

Figure 8: Adding a new node

Receivers are matched with their node counterparts in the configuration page using an ID (such as 5 as shown in Figure 8). This is set when the receiver software is run, and also when creating a node using the configuration page. These must match for the system to work correctly. Implementing the management of receivers and nodes this way allows for them to be decoupled. Using this method, receivers can be added to or removed from the system without interrupting the rest of the system, regardless of whether a corresponding node has been created.

In addition to configuring receivers, in order for the system to correctly convert between the Google Maps co-ordinate system and real metres, two calibration markers need to be set. This is done by right-clicking the page and adding a new calibration marker as shown in

Figure 9 below. Calibration markers appear as a green colour. Calibration marker names must use “start_X” and “end_X” where X is replaced with the distance between the two calibration points in metres.

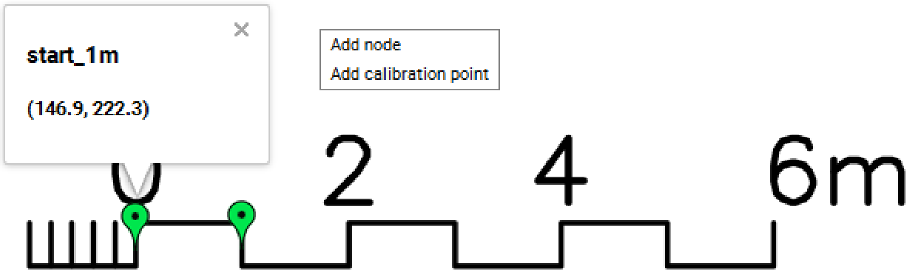

Figure 9: Adding a new calibration point

4.3.3 Display Component

The display component is designed to intuitively visualise the area that a Wi-Fi device is most likely to be found inside of. These areas are shown on the map as a circle with a marker placed in the centre as shown in Figure 10 below.

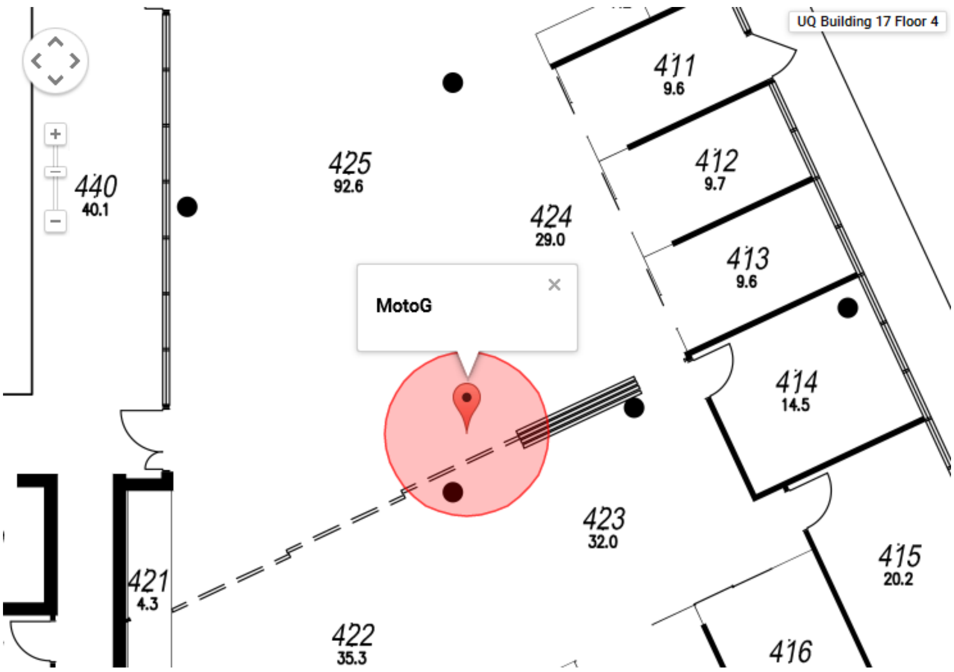

Figure 10: Wi-Fi device position display

The map display updates in real-time without any action necessary by the user. This is achieved by using MQTT as an event messaging system so that the display component will receive events related to new device positions. The circular area around a device marker will grow or shrink depending how accurate the position is.

5. Results and Discussion

5.1 RSSI Ranging Accuracy

The RSSI distance model is the main key factor within a Wi-Fi indoor positioning system that affects overall position accuracy. If the distances generated by the model are significantly different to the actual distance, then this will greatly decrease the overall system accuracy. Figure 11 below, shows a graph of the RSSI for three different smartphones over 5 metres. As can be seen, there is a high degree of variability between different smartphones, up to 10 dBm in some cases. This is due to a number of factors including different antennas and radio modules used in each phone, as well as some intrinsic measurement error due to how noisy Wi-Fi RSSI measurements are.

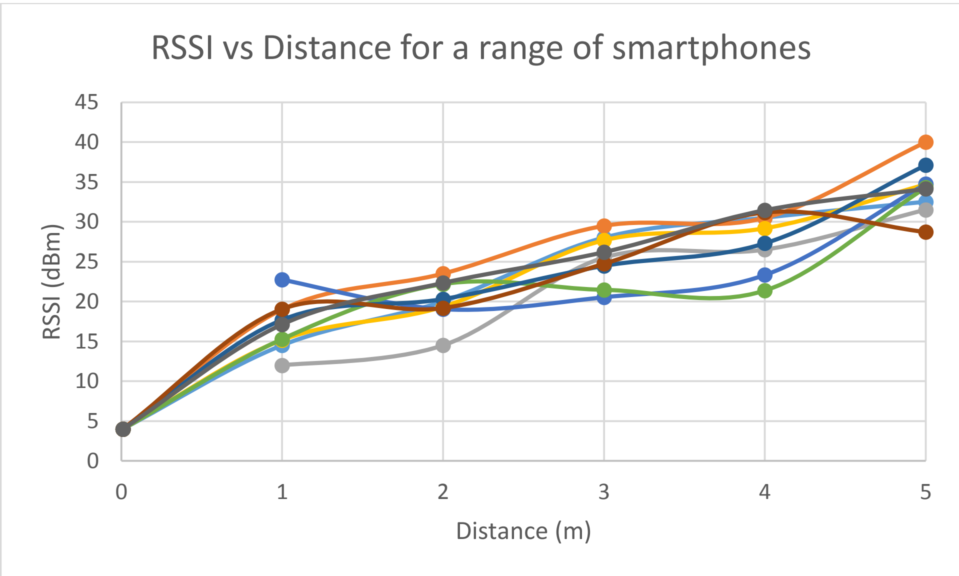

Figure 11: RSSI vs Distance for a range of smartphones

This testing was performed in a relatively unobstructed environment with a single doorway between the receiver and smartphones at the 2.5 m mark. The receiver and smartphones were placed on two chairs of the same height so as not to affect the distance measurement. Wooden chairs were used in order to minimise any signal interference. RSSI values are the result of averaging RSSI readings for a minute at each distance. In order to capture data more quickly, each smartphone was continuously pinged using another device on the Wi-Fi network in order to create more Wi-Fi traffic for the receivers to listen for.

Using these RSSI readings, the constants in the log-distance model were calculated in order to calibrate the model. Using the calibrated log-distance model, the RSSI values collected can be transformed into distances and compared to the actual measured distances. The average distance error using this method is up to 1.4 m. All data is included in *Appendix A – RSSI Ranging Results*.

The results achieved for the RSSI ranging and distance model are reasonably good over short distances (up to 5 m). There is of course, some variability arising from the differences between the phones themselves. This means the log-distance model is calibrated for the average of the RSSI values recorded, so the log-distance model will never be ideal for every smartphone. Nonetheless, the level of accuracy achieved for these three different smartphones is reasonable.

In addition to the variability between different smartphones shown above, there is some variability introduced by the Wi-Fi adapters themselves, despite all of them being the same model. Figure 12 below, shows the RSSI value vs distance for each of the five receivers in the Wisn system. All data is included in *Appendix A – RSSI Ranging Results*.

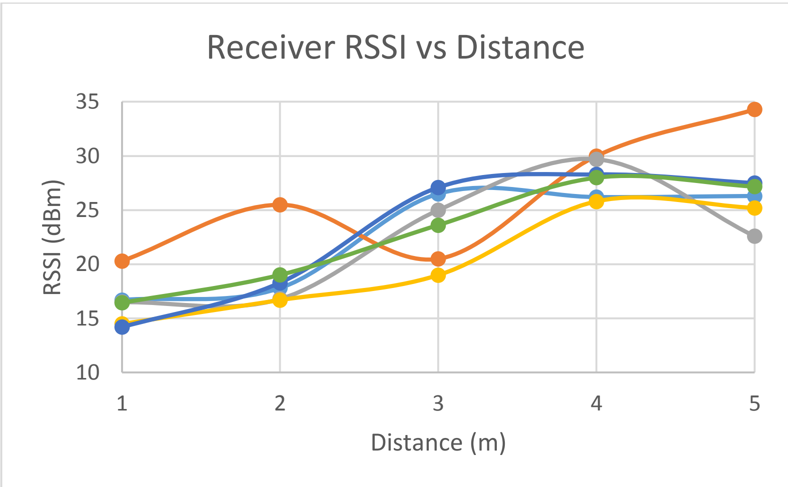

Figure 12: Receiver RSSI vs Distance

This test was performed in the same way and under the same conditions as the RSSI ranging test, however only a single smartphone was used in order to keep the transmission level constant. As can be seen, there are significant differences in the received signal strength (up to 11.7 dBm) of different Wi-Fi adapters despite all using the same transmission source, antenna and model. The RSSI at each receiver should be very comparable (with 1-3 dBm) under these circumstances, so this large disparity can only be put down to differences in construction of the Wi-Fi adapters and their antennas, since all other factors should be constant.

This additional uncertainly also adds to the overall positioning error of the system. The variability between receivers means an average distance error of up to 2.5 m is possible at a 5 m distance. This appears to be greater than would be expected, however aside from testing a greater sample of Wi-Fi receivers and antennas, there isn't likely to be a simple solution to this problem. Using separate log-distance models calibrated for each receiver may provide some accuracy improvement, however it would also increase the complexity and calibration costs of the system quite a bit, particularly for large systems with many receivers.

5.2 Position Accuracy

The overall positional accuracy of the Wisn system is difficult to measure accurately. This is because aligning real world measurements with those in the Google Maps display interface can be a tricky job. As such, all results presented here include more measurement error than would be expected, since all measured positions from the display interface were taken by eye.

The positional accuracy of the Wisn system was tested in two environments. The first consisted of a square 4 x 4 m area with three receivers placed in a triangle as shown in Figure 13 below. The area consisted of a fairly unobstructed lounge room with some furniture throughout. The walls surrounding this area were double-block walls.

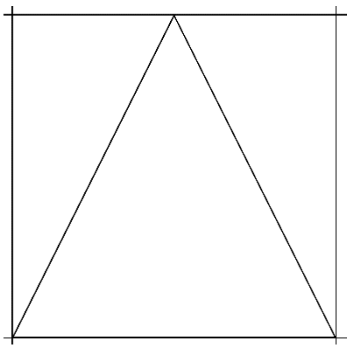

Figure 13: Receiver positions form a triangle inside the square area

A smartphone was placed at a number of different positions within the area and the position of the device calculated by Wisn was recorded. No people were present in the room while the measurements were taken. All data is included in *Appendix B – Position Accuracy Results*.

The average positioning error for this test was 0.75 m. This is quite a low distance error, however it must be remembered that there are a number of factors at work here that help Wisn. Firstly, the area itself is as close as possible to a perfect environment for using Wi-Fi positioning systems. It is a relatively unobstructed environment where RSSI values follow very closely to the log-distance model.

Additionally, the longest length within the area to be tracked is the diagonal from one corner to another, a distance of approximately 5.6 m. This distance is relatively short, so interference and other variability have less impact on the distance calculations. To put it another way, because of the logarithmic nature of the model, a small change of 1 – 2 dBm may only change the distance by 0.5 – 1 m at short distances. At long distances however, the same 1 – 2 dBm difference might change the distance by 5 – 10 m.

The second area where the Wisn system was tested is more indicative of a real world environment where the system might actually be used. The area was approximately 8 x 10 m and was an open office floor, style environment. As can be seen in Figure 14 below, there was a removable wall positioned between the receivers. There were also a range of furniture including desks, tables and chairs as well as computers, TVs and other assorted technology placed throughout the area. It is also important to note that the whole floor is surrounded by glass windows which have a metallic coating.

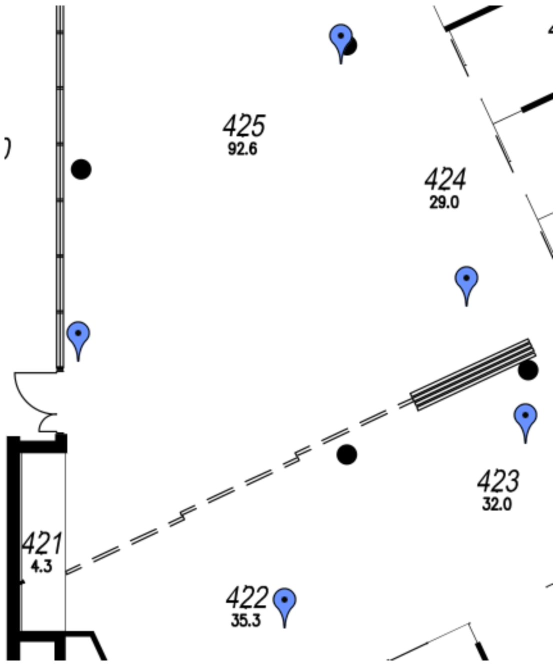

Figure 14: Receiver positions for 8 x 10 m area

As with the previous test, a smartphone was placed at a number of different positions within the area and the position of the device calculated by Wisn was recorded. There were a small number of people walking around the area (4 – 5) while the measurements were taken. All data is included in *Appendix B – Position Accuracy Results*.

The average positioning error for this test was 2.4 m. This is much closer to the expected positioning error of 2 – 3 m that other Wi-Fi based positioning systems achieve. The major reasons for the increase in positioning error compared to the first test is because the size of the tracking area has been scaled up. Despite adding more receivers, the longest distance inside the bounds of the receivers is now almost 13 m. At these distances, small changes to RSSI values can make large changes to the calculated distance.

In addition to this, there are now many more obstructions present in the environment including people walking around and walls. The windows that surround the floor also interfere with the Wi-Fi signals. This is because they are metallic coated and thus reflect Wi-Fi signals much better than normal glass would.

Of particular note is the distance error observed for location 7. The smartphone was placed on top of an aluminium-bodied laptop at this location and as can be seen, this completely ruins the position accuracy. This just goes to show how sensitive Wisn and some other RSSI based positioning systems are to seemingly small changes in the environment.

6. Future Direction

While Wisn is a fully functional passive, Wi-Fi-based indoor positioning system, there are a number of areas in which it could be improved upon. This section describes some key ideas that could be implemented to either improve accuracy and reliability, or the user experience.

6.1 802.11n Wi-Fi Receivers

Wisn made use of 802.11g Wi-Fi receivers due to the excellent receive sensitivity provided by them. The trade-off was of course that not all 802.11n traffic would be captured. Now, with the benefit of having tested the wireless adapters, for shorter range situations (less than 15 m) it may not be necessary to pick the 802.11g adapters with high receive sensitivity over the 802.11n adapters, because even lower sensitivity receivers should be able to receive Wi-Fi transmissions a those distances. Upgrading the receivers to 802.11n wireless adapters would allow for a larger portion of Wi-Fi transmissions to be received and thus increase the ability of the system to accurate track devices.

6.2 Integration with Access Points

During development of Wisn, a choice was made to ensure that the receiver software would be as lightweight as possible so that it could be integrated with access points in the future. While no testing has been performed, the Wisn receiver software should be able to be compiled and run on the common Linux based firmware for routers, OpenWrt with some small tweaks. This would allow for the access points to serve a dual purpose and provide a wireless network connection at the same time as being able to track Wi-Fi devices. This helps make Wisn better value because it is able to take advantage of potentially pre-existing infrastructure or provide a service other than Wi-Fi device tracking.

6.3 Receiver Control Centre

Throughout the development of Wisn, one of the most time consuming parts was updating, configuring and restarting receivers individually. A future improvement would allow for all receivers to be controlled via a web-based control centre. The Wisn receiver software could easily be extended to do this by leveraging MQTT to send events and notifications. This would easily allow administrators to update the whole system or tweak some values without having to individually connect to each receiver at a time.

6.4 More Accurate RSSI Distance Model

One of the limiting factors as to how accurate RSSI-based positioning systems are, is the RSSI distance model. The log-distance model implemented in Wisn is a good compromise between a very simple model, and a very complex one. By exploring and implementing a more complex model (perhaps one that uses statistical methods) the accuracy of the system for a wider variety of situations may be improved.

6.5 Weighted Multilateration Model

One of the biggest problems with standard multilateration is that when used for a large system, no matter where a Wi-Fi device is, it will always be far away from at least one receiver. The problem is that, as already described, small RSSI changes when far away means large changes in distance calculations. These large distances can act as outliers and cause multilateration to give inaccurate positions. One of the simplest ways around this is to give a weight to each of the distances calculated, based on their RSSI value. This would allow shorter distances to be weighted higher than longer distances, and help to minimise the effect of long distance ranging errors.

6.6 Alternative Display Interface

Google Maps was chosen as the mapping API of choice for Wisn because of how familiar it is to users as well as providing other mapping services. The major downside to Google Maps currently is that it does not support flat maps, such as those used by Wisn, very well. Ideally, xy-coordinate support could solely be used for placing markers and drawing objects, however Google Maps uses latitude and longitude for all of these tasks. It does provide a world coordinate system which acts very similarly to xy-coordinates, however they can only be used by converting latitude and longitude points and they must be converted back to latitude and longitude for all mapping related tasks. An alternative system that allowed for a simple xy-coordinate system may help reduce some of the complexity for the web interface.

7. Conclusion

Before development of Wisn began, a number of different indoor positioning system technologies were reviewed. The decision to use a passive Wi-Fi-based indoor positioning system was motivated by the aims of being low cost, low power, and easy to setup and use. Wi-Fi based positioning systems are not the most accurate system available, however they strike the best balance between accuracy and cost.

Wisn was developed with the goal of working with as much pre-existing infrastructure as possible and using a modular design. This allows for each of the three parts of Wisn, the receiver, the central server and the display system, to all work independently and could even be replaced or upgraded in the future without having too much of an effect on the other parts.

The performance of Wisn in a real world environment is about the same as many other RSSI-based indoor positioning system; that is 2 – 3 m accuracy. The many issues facing Wisn is the variability that arises from different models of smartphone as well as consistency issues with the Wi-Fi adapters used. A range of improvements to the system have been suggested in order to improve upon these aspects of the system.

Appendix A – RSSI Ranging Results

Table 4: RSSI vs Distance results with a range of smartphones

Distance (m)	0.01	1	2	3	4	5
Nokia 530 #1 (dBm)	4	14.5	20	28	30.5	32.5
Motorola Moto G #1 (dBm)	4	19	23.5	29.5	30.5	40
Nokia 630 #1 (dBm)	-	12	14.5	25.5	26.5	31.5
Nokia 530 #2 (dBm)	4	15.16667	19.33333	27.66667	29.16667	34.66667
Motorola Moto G #2 (dBm)	4	15.28152	22.18587	21.46756	21.368	34.2861
Nokia 630 #2 (dBm)	-	22.74479	19.03403	20.53734	23.32576	34.74332
Nokia 530 #3 (dBm)	4	19.0495	19.18182	24.73504	31.18182	28.71818
Motorola Moto G #3 (dBm)	4	17.69841	20.30435	24.47619	27.29825	37.10345
Nokia 630 #3 (dBm)	4	17.12291	22.32484	26.18954	31.45223	34.12571
Max difference (dBm)	0	7.578125	3.290809	7.129326	10.08423	8.385266

Table 5: Calculated distances using calibrated log-distance model and RSSI values from Table 4

Distance (m)	0.01	1	2	3	4	5
Nokia 530 #1 (m)	0.275423	0.724436	1.202264	2.511886	3.162278	3.801894
Motorola Moto G #1 (m)	0.275423	1.096478	1.659587	2.884032	3.162278	7.585776
Nokia 630 #1 (m)	-	0.57544	0.724436	1.995262	2.187762	3.467369
Nokia 530 #2 (m)	0.275423	0.770312	1.130663	2.43594	2.796834	4.641589
Motorola Moto G #2 (m)	0.275423	0.778504	1.470398	1.376266	1.363703	4.481711
Nokia 630 #2 (m)	-	1.548074	1.09992	1.263263	1.633166	4.674473
Nokia 530 #3 (m)	0.275423	1.101489	1.114995	1.859524	3.36723	2.683659
Motorola Moto G #3 (m)	0.275423	0.972605	1.236442	1.815715	2.354669	5.809489
Nokia 630 #3 (m)	-	0.922393	1.489339	2.12609	3.452146	4.415995
Worst Absolute error (m)	0.265423	0.548074	1.275564	1.736737	2.636297	2.585776
Average error (m)	0.265423	0.056697	0.763551	0.970225	1.391104	0.382005

Table 6: Receiver RSSI vs Distance

Distance (m)	1	2	3	4	5
Wisn1 (dBm)	16.7	17.8	26.5	26.2	26.3
Wisn2 (dBm)	20.3	25.5	20.5	30	34.3
Wisn3 (dBm)	16.5	16.8	25	29.7	22.6
Wisn4 (dBm)	14.5	16.7	19	25.8	25.2
Wisn5 (dBm)	14.2	18.3	27.1	28.3	27.5
Max Difference (dBm)	6.1	8.8	8.1	4.2	11.7

Table 7: Calculated distance using calibrated log-distance model and RSSI values from Table 6

Distance (m)	**1**	**2**	**3**	**4**	**5**
Wisn1 (m)	0.887156	0.981748	2.187762	2.128139	2.14783
Wisn2 (m)	1.235947	1.995262	1.258925	3.019952	4.487454
Wisn3 (m)	0.870964	0.895365	1.905461	2.93765	1.527566
Wisn4 (m)	0.724436	0.887156	1.096478	2.051162	1.940886
Wisn5 (m)	0.704693	1.028016	2.312065	2.58226	2.398833
Worst Absolute Error (m)	0.295307	1.112844	1.903522	1.948838	3.472434
Average Error (m)	0.115361	0.842491	1.247862	1.456167	2.499486

Appendix B – Position Accuracy Results

Table 8: Positioning measurements for a 4 x 4 m area using 3 receivers

All measurements in metres	**Real x Position**	**Real y Position**	**Measured x Position**	**Measured y Position**	**Error Distance**
Location 1	0.5	0.5	0.9	1.1	0.721110255
Location 2	2	3.5	2.5	4.2	0.860232527
Location 3	2	2	1.7	2.3	0.424264069
Location 4	4	1	3.2	0.4	1
Average					0.751401713

Table 9: Positioning measurements for an 8 x 10 m area using 5 receivers

All measurements in metres	**Real x Position**	**Real y Position**	**Measured x Position**	**Measured y Position**	**Error Distance**
Location 1	1	1	3.1	1.6	2.184032967
Location 2	7.8	1	6.9	2.3	1.58113883
Location 3	7.5	4	4.4	3.6	3.125699922
Location 4	7.5	9.8	6.7	8.9	1.204159458
Location 5	0.2	5.7	0	6.5	0.824621125
Location 6	4	6	2.6	3.5	2.865309756
Location 7	2	1.5	3.6	-3	4.775981575
Average					2.36584909

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