Assessment of LoRa and IEEE802.15.4 suitability for asset tracking across an urban environment.

A study comparing the power and cost of IoT devices and GPS receivers.

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Declaration

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Acknowledgments

The journey to this report has been long and arduous and has not been done by one person alone.

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Abstract

This report will investigate the effectiveness of IEEE802.15.4 and LoRa localization in an urban environment. This was done by dynamic mapping using Received Signal Strength Indicator(RSSI) values obtained by sending packets in a four-node personal area network. The purpose behind this investigation is to see if the Internet of Things (IoT) networks used would be able to produce results that are as accurate as those given by GPS receivers in an urban environment such as a city or town both indoors and outdoors. Other metrics that will be evaluated will be the cost of the infrastructure and the power consumption compared to the GPS network. The proposed system in this report may easily be implemented in existing networks to allow the location of the nodes in that network as well.

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Chapter 1

Introduction

1.1 Background to the study

Localisation is a means by which an end device or central gateway device, obtains its geographical location or the geographical location of other devices in the network(in the case of the gateway). This has been an important concern in the modern era for navigation and guidance systems and tracking for both military and civilian purposes. This could include tracking packages, vehicles as well as humans in various environments. Currently, this field is dominated by satellite technologies that are useful for large-scale use but can have the same quality if not better be achieved using a less power hungry and cheap system.

This report will lightly touch current localisation technologies available through Internet of Things (IoT) devices. It will then cover a more comprehensive comparison of two of these IoT devices relative to a satellite technology and how the two compare regarding accuracy, power consumption, and cost. Such testing would be done in the context of moving objects in an urban environment both indoors and outdoors. These technologies may be useful in tracking packages and assets over large factories or multisite facilities. For instance, a specific batch of stock is being moved from an assembly or manufacture plant to a storage facility. To keep track of this batch and find it when needed and to ensure its availability.

1.2 Objectives of this study

1.2.1 Problems to be investigated

This study will be comparing a modern day implementation of the Phone Based Global Positioning System (GPS) to two Low Power Wide Area Networks (LPWAN) in an urban environment. It will also look to optimise the power consumption and data collection simultaneously given that the devices are battery powered hence reducing the number of recharge cycles. The accuracy of these devices will also be put to test as this is the most important statistic in localisation. Finally, the cost of the infrastructure and deployment of the supporting networks will also be put to question.

1.2.2 Purpose of the study

This study will contribute to the current body of knowledge regarding cheaper and lower power localisation by way of non-GPS devices. While ubiquitous GPS radios are very power hungry, more expensive and less accurate indoors, an alternative radio would be ideal if it could perform better. This report will cover two alternative approaches for localisation using commercial RF communication signals through the design and implementation of their respective tracking node devices and experimental data capture under real-world representative operational conditions. The final goal will be to select the best IoT network for asset tracking across a multisite factory in a city.

1.2.3 Research objectives

At the end of this project, it is expected to have achieved the following:

1. Build and implement a LoRa and IEEE802.15.4 Network
2. Implement efficient localisation algorithms for LoRa and IEEE802.15.4
3. Evaluate and compare each network's localisation error, power consumption, cost, expected lifespan and effectiveness for the use case against a GPS network.
4. Select the best network for the intended use case

1.3 Scope and Limitations

This project will look at the simultaneous construction and use of two different LPWAN systems that will use trilateration to obtain the location of the end device using it alongside phone-based GPS. This report will also cover the most vital metrics of each technology and how they compare to each other.

With a project budget of R1500, the technologies used will have to fit into the budget to allow tracking that is within 20% of phone-based GPS tracking.

Due to ICASA[5] regulations regarding frequency and power limitations, some radio technologies will not be considered for use as the radio equipment is not legal for use in South Africa or has not been rolled out and deployed in Cape Town.

1.4 Plan of development

Chapter 2 of this report presents a literature review that will cover some of the work that has been done in this area. It will also introduce some of the key concepts that will be used in this investigation. The chapter following that will show how the experimental set-up was created and the requirements that it needed to fulfil. The testing strategy will then be presented, followed by the results of the tests that were conducted. Finally, a discussion of the results and conclusions will be presented alongside some proposed areas of further development for future researchers.

Chapter 2

Literature Review

This chapter will look at some of the core foundations and goals of IoT devices and how they may be used. The core concepts behind localisation will be presented, followed by a study of how GPS works and how it has been developed to adapt to power limitations. What will follow this is an in-depth look at some common IoT technologies and some of the work that has been done regarding localisation will be presented. A review of some possible localisation algorithms and metrics will then be given and briefly discussed, which will be followed by a look at power consumption and some of the work that has been done in this field. Finally, the specific gap in this field of localisation that this report will aim to cover.

2.1 IoT Devices

The goal behind IoT is to have sensors in a network collect data and send it for processing such that there is less time spent doing so manually as that may pose risks and hazards or be an unnecessary strain. A more succinct definition of these devices was given by Ma [6] as he cites that these devices fulfil three basic criteria. They can:

1. Instrument ordinary devices
2. Connect autonomic terminals
3. Allow intelligent services

Having understood these requirements, it can be said that these devices are versatile, multipurpose and smart. They help in distributing the workload that may exist at a central terminal by simplifying the work that needs to be done.

These devices are used in multiple different areas of industry that include home automation as shown by Kodali et al.[7] and Jabbar et al.[8], security and monitoring[9], metering systems[10], leak detection[11] as well as for localisation[12][13] as shown in this report.

In Jabbar et al.'s report[8], the authors focus on implementing a high data rate IoT network that will be cost effective and easily accessible for use by implementing device control over an IEEE802.11 network(WiFi). Gupta and Johari[9] extend this same concept by additionally showing that IoT devices can be versatile enough to be cloud based and used to monitor street lights and help in conserving energy usage. They also bring up the idea that these networks can work on a variety of standards and protocols such as Message Queuing Telemetry Transport (MQTT), Hyper Text Transfer Protocol (HTTP), and many other machine-to-machine (M2M) protocols.

Regarding Purnama and Nashiruddin's work[10], the authors focused on planning the metering system to rely on the data captured by IoT devices and relay this information by way of LPWAN devices. This estimation showed the possibilities and the required infrastructure for this to be theoretically successful in three different areas of Indonesia. Afifi et al.[11] use a similar approach of distributing nodes around a city network of water pipes that will be used to help with leak detection. This was based on the data from Hurghada, Egypt, and showed the use of a Kalman filter to help make the system adaptive and responsive to new conditions that could indicate a fault in the pipes.

2.2 Localisation

Localisation is the means by which a location is obtained from a supporting network infrastructure. This network stack may be linked to satellites, various base stations, or even surrounding devices. The overarching idea is to therefore give a location based on the position of the base stations. This concept is useful in tracking and navigation. Ramnath[13] explores this further by covering some of the methods that may be used to achieve this as well as some general commentary on the area. One key observation is that this functionality can be added on to existing IoT deployments.

Various methods are being used to fulfil this need that range from different network stacks to varying algorithms that support these networks in this job. An international standard for this would be the coordinate system used by the GPS[14]. This system has undergone some of its own refinements through services such as 'what3words'[15]. The latter uses 3 words to define the position of a receiver as opposed to the former, which utilises two strings which comprise the latitude and longitude. Building from these two, it can be seen that many systems can be built around the infrastructure they utilise.

2.3 Localisation infrastructures

2.3.1 Global Positioning System (GPS)

The GPS is reliant on multiple satellites currently orbiting in space to calculate the position of one of its receivers.[16][17]. This relies upon a line-of-sight connection to multiple satellites, making it very precise in outdoor environments, however very terrible for indoor usage.

By way of resection and intersection, the receiver will be able to determine its location string and deliver it to the host device. This is achieved by the GPS satellites constantly emitting signals that receivers can pick up. This signal includes two sine waves and digital codes.[16] At the time of authoring, there are 31 operational satellites in the GPS constellation of which at least four are visible from any point on earth. Figure 2.1 shows some of the satellites that were providing service to Cape Town at the time of authoring this report.

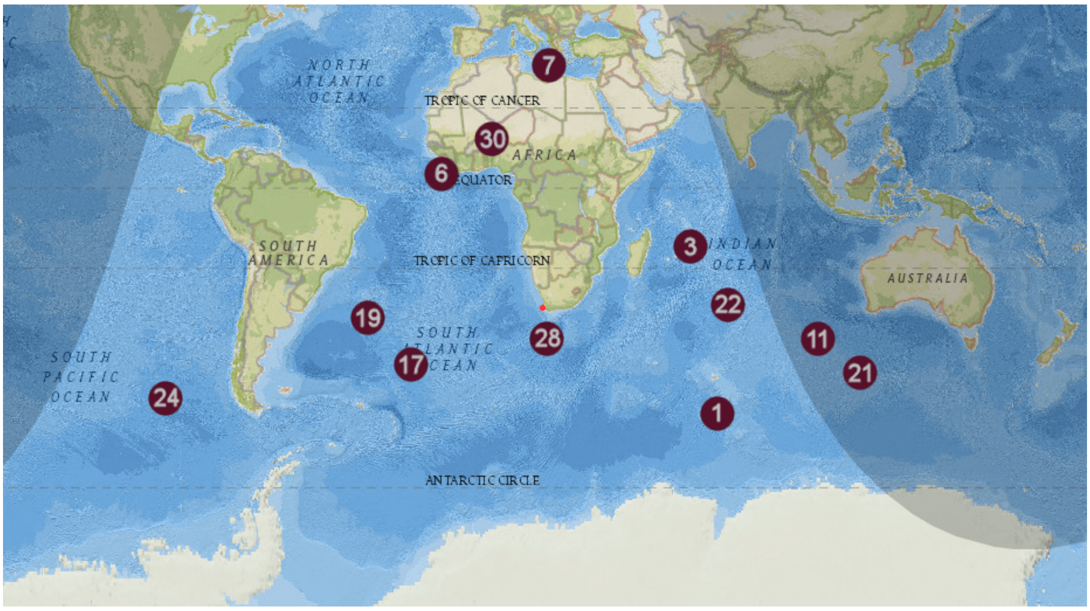

Figure 2.1: GPS satellites servicing the areas surrounding Cape Town on 9 November, 2020. Image and data obtained from N2YO

Assisted GPS (A-GPS)

This is a refinement upon the traditional GPS infrastructure and is implemented by mobile devices, mainly cellphone networks[18][19]. The term 'assisted' comes from the fact that the phone will incorporate the Code Division Multiple Access (CDMA) infrastructure to help determine a location. This leads to lower acquisition times a.k.a. Time To First Fix (TTFF), and in some cases, a lesser need for the minimum number of GPS satellites to get a signal. In [18], the goal was to investigate the differences between GPS and A-GPS and the conclusion was that similar results could be obtained but with greater errors in accuracy. Considering that these services were mainly used in emergency cases, the results were acceptable coming within 100m of the true location.

Ma et al.[20] explore the possibilities of using Wireless Local Area Networks(WLANs) to achieve the same results for indoor localisation. They proposed a solution that would step in when a processor that had access to a WiFi radio and GPS receiver with less than four active satellite connections. If the GPS receiver had more satellites available, the WiFi network would merely provide further accuracy and 'assist' the main GPS receiver.

Ramos et al.[19] further explored this idea by experimenting with LEAP (Low Energy Assisted Positioning), a combination of GPS, cell towers and cloud computing to help reduce the energy cost of GPS localisation. This was achieved by turning on the receiver for 500ms and using a cloud server by way of cell towers to obtain the rest of the location data. This led to similar accuracy to the ordinary GPS modules that are always on with less power used.

A more recent study performed by Dinh[1] proposed a solution to issues with the power consumption of GPS receivers. This proposed that the receiver be on for substantially lower amounts of time and measurements be taken periodically. The results of this were acceptable accuracy that came close to commercial receivers but also a longer battery life for the equipment used when compared to another receiver that did not implement the newer algorithm.

2.3.2 LPWAN

As mentioned before, IoT devices are known for their ability to send data within their networks. Through using simple data transfer and geometry, it is possible to start working on collecting information about a device's location.

There exist many versions of such localisation using multiple network stacks such as Zigbee,IEEE802.15.4, Bluetooth, LoRa among others[12][21][22][23][24][25][26][27][28][29]. In some cases, researchers sought to improve the algorithms used in obtaining location data [23][24][28][30][31] as localisation is not a common use case for IoT devices. Some of the work in relating to LPWAN localisation will be covered in sections relating to the different network stacks below.

Bluetooth Low Energy (BLE)

BLE is based on the classic Bluetooth technology that had previously existed. This was pioneered by Ericsson which partnered up with Nokia, IBM, Toshiba and Intel to create an over-the-air and low power system to transmit data.[27]

In 2011, the BLE standard was released, Bluetooth 4.0, and unlike its predecessor, it used much less power as a result of a sleeping receiver(slaves) that are only awake when transmitting.[32] This significantly dropped the power usage and revolutionised the industry.

Regarding localisation, Farnham[21] worked on implementing BLE in situations where line of sight was not possible. This was done alongside WiFi using the angle of arrival and machine learning method to obtain a location. It was found that with a high number of BLE access points, there was a lower likelihood of path loss errors in the data. It must be noted here that BLE was used to simply compare to WiFi and was not the focus of the paper.

BLE was however the main focus in Leong et al.'s[22] test's. Here it was shown that BLE, by way of basic RSSI measurements, can achieve good accuracy and that the only limitation to the investigation was the number of zones chosen to experiment with. The experiment with 100 zones was chosen, but if divided into more, the accuracy of the location approximation would be improved.

IEEE802.11 (Wi-Fi)

This is one of the most commonly used means of communication today as it is used by many of the world's public. There are a multiple physical layer protocols under it. More recent advances led to IEEE802.11ah (Wi-Fi HaLow), which is a low power implementation of the protocol.

Looking back at Farnham's report[21], the results were in line with the conclusion from the BLE tests showing that localisation was possible and was accurate. With the focus being on fingerprinting and dynamic radio environment mapping, the proposed improvements to those areas would greatly improve the results of the study.

IEEE802.15.4

This standard was defined in 2003 and was defined to provide a low bandwidth, low power and low cost data delivery service. This standard has been further developed into many other technologies that define the upper network layers.[33] These include Wireless HART, 6LoWPAN and Zigbee(which is discussed below).Al Mamun et al.[25] produced some work looking into Radio Mapping on devices that used this protocol.

In this paper [25], it is seen that IEEE802.15.4 localisation is very possible and is supported by the results and methodology with a single reference node. Using fingerprinting, the data showed errors of up to 1m within the test zone.

Zigbee

Zigbee was born out of IEEE802.15.4 but extends its functionality by defining more protocols above the base standards. This includes the addition of 'players' in the network, known as the router coordinator and the end device.

Deseada et al.[26] performed some indoor mapping investigations to see its suitability for this use case. These tests used a fingerprinting method to locate a device in an environment. The main goal was to however implement the system and no substantial data was collected.

Long Range (LoRa)

One of the biggest LPWANs today that has caused a lot of talk has been LoRa with its very low data, low bandwidth and low power transmission. These devices led to the creation of multiple LoRaWANs (LoRa Wide Area Networks) that allow data to be received at gateways and uploaded online for users. Many aspects of this technology have been looked at, but Henriksson[27] and Choi et al.'s[28] work will briefly be discussed as it pertains to localisation.

In Henriksson's[27] simulations, the conclusion was that working with LoRa was very possible and the thesis looked at the different methods available for doing so. The main take away was, however, the use of LoRaWAN to obtain some of the data that exists in every packet to find its location. Finally the error from the RSSI localisation was 8m at best.

Regarding Choi et al.'s [28] report, the goal was the same as Henriksson's but with a privately defined WAN. In this, the radio environment was constantly measured and machine learning was used for the algorithm. The end result was an accuracy of 24.1m. What was also found was that the cost and power used in the localisation was greatly reduced as a result of using LoRa.

Narrow Band(NB)-IoT

NB-IoT is a low bandwidth, low data network that relies on mobile network infrastructure. NB-IoT, like other networks, is low cost and low power but has a longer range than many others. Janssen et al.[29] covers some extensive tests to find how accurate localisation may be. After evaluating multiple algorithms to achieve this, the mean average error was found to be 204m. It is important to note that this study was done in an urban environment.

Other LPWANs

Many other LPWANs exist and because of the algorithms and methods available for localisation, most of them can be used for that purpose. Some of the others are derived from the LPWANs that have been discussed above, such as Sigfox, which is derived from LoRa. Another option may have been Weightless, which is a more recent development and not much work has been done in this area.

Another option would have been Ultra Wide Band, which has a different approach from the other networks discussed. As derived from the name, this uses a higher bandwidth but remains cheap and not power hungry. Beuchat et al.[12] examined localisation with such a different network and the results were outstanding with mean errors in the order of tens of centimetres.

Algorithms

As much as it was important which LPWAN would be used, the algorithm of obtaining a location would be pivotal as this often affects the interpretation of the data and the accuracy of the localisation. Multiple methods exist to achieve this and have ranged from computationally intense and power hungry to very simple and less power intensive. This is not to say that these two sides may not intersect, but the key objective has been to improve the accuracy and precision of these techniques. These techniques range from measured metric-based systems[30] to machine learning reliant applications[28] and can rely on a processing step in some cases. This can be implemented in the cloud, separating processing devices and data collection.

Measured metric-based systems These systems are all usable with triangulation or trilateration as a means of obtaining the final location.

Receive Strength Signal Indicator (RSSI)

The RSSI measures the signal power that a packet arrives at a receiver with. When transmitted, a packet's strength will diminish as a result of the obstacles it needs to get through and the distance it needs to travel. Other external factors, however, affect this metric such as temperature, humidity, and other networks in the area that are utilising the same radio frequency band. The key formula associated with RSSI is:

$$Z = Z_0 + 10n \log_{10} d + A \tag{2.1}$$

where Z is the receiver signal strength, Z_0 is the receiver signal strength at 1m, d is the distance we are calculating and n is the loss exponent, and finally A is a random Gaussian variable representing the background noise. Another way of looking at this value is to look at the power lost in transmission:

$$Z = P_{transmit} - P_{receive} = 10n \log_{10} \frac{P_t}{P_r} \tag{2.2}$$

Time of Arrival (ToA)

This method involves accurate timing to find how much time it takes for the message to be received after being sent. This is simple in calculation but requires accurate timing which may need more costly hardware. The simple formula behind this is:

$$d = c * t \tag{2.3}$$

where d is the distance between the transmitter and the receiver, c is the speed of the signal being sent and t is the time it takes to send this signal.

Time Difference of Arrival (TDoA)

TDoA builds on ToA by only looking at the base stations point of view. By calculation, the difference in times that the stations receive the same packet, the distance from the stations can be calculated. This is done using the equation 2.3.

Time of Flight (ToF)

ToF is also based on the concept of the amount of time it takes for a packet to travel like ToA and TDoA. The main difference is that it measures the Round Trip Time (RTT) of a packet and infers a distance measurement based on a modified version of equation 2.3:

$$d = \frac{c * RTT}{2} = \frac{c * (t_{rec} - t_{sent} - t_{proc})}{2} \tag{2.4}$$

where t_{rec} is the time that the packet is received at the initial sender, t_{sent} is the time the packet was initially sent and t_{proc} is the time it takes for a base station to receive and send a message.

Angle of arrival (AoA)

This technique relies on two receiver antennas picking up a packet and as a result of the time difference, based on the TDoA technique, the distance from the receiver can be obtained and furthermore, the location of the sender. This technique proves to be a bit more power and cost intensive on the receiver's end as two radios and antennas are needed.

Hybrid

It must also be noted that hybrids of the listed metrics may be used as well to obtain location information about a receiver's location. A very comprehensive study of these was conducted in Laaraiedh et al.'s[31] investigation where various combinations of RSSI, ToA and TDoA were used. The experiments were done using UWB and the conclusions stated that RSSI was useful in cases where ToA or TDoA data was not readily available, but ToA and TDoA were where the most accuracy was found.

Processing steps

Dynamic Mapping

This involves mapping the environment that the system will be used in and populating a database with the data. When searching for a position, the database will be searched for the values of the measured metrics that match those obtained and the position is given. Farnhanm[21] combined the AoA technique with Dynamic Mapping to obtain results that were very impressive as discussed earlier. These were compared to results based on indirect mapping, which was done by calculation the expected path loss and inferring a distance from that data. Estimation came close to the real value provided an extra correction factor was added to the initial path loss formula.

Fingerprinting

Fingerprinting uses machine learning to infer a position based on some stored locations within a database. Often used is the K-Nearest Neighbours technique to obtain the final position. This processing step is implemented in Deseada et al.'s[26] with Zigbee and RSSI, which Choi [28] implemented this with RSSI and TDoA with LoRa as the LPWAN of choice.

Statistical Analysis

This processing step uses statistical methods such as the Maximum Likelihood(ML) estimator or the Weighted Least Squares(WLS) method.

WLS uses the following base matrix calculation:

$$\hat{X} = (A^T C^{-1} A)^{-1} A^T C^{-1} \tag{2.5}$$

Where A, b and C are matrices defined as per each measured metric.

Both of these are used by Laaraiedh et al.'s[31] to see which yields the best results. The results showed that the ML method was better in all cases regarding accuracy. What is key about these methods is that they often are mathematically intensive, so a powerful processing unit is needed.

2.4 Power Consumption

One of the key factors in this report will be looking into the power consumption of the devices that are being used. This is because when looking at the power used by the average GPS module, long-term use of a single battery cycle is not easily achieved unless there is a modification in the protocol as shown by Dinh[1] and advances such as LEAP which is a modification done by Ramos et al.[19]

A key source for general metrics on this information can be found in a data sheet where values can be quoted to indicate the expected current draw at specific operational voltages and in specific modes if available. In the case of LEAP[19], it takes advantage of varying the duty cycle of an ordinary receiver such that the average current drawn every minute is decreased.

Dinh[1] takes a different approach by using a snapshot obtained from the towers as opposed to the always on receiver and reduces the collection time. This lead to better accuracy and a decreased current draw. Figure 2.2 shows the results of the study.

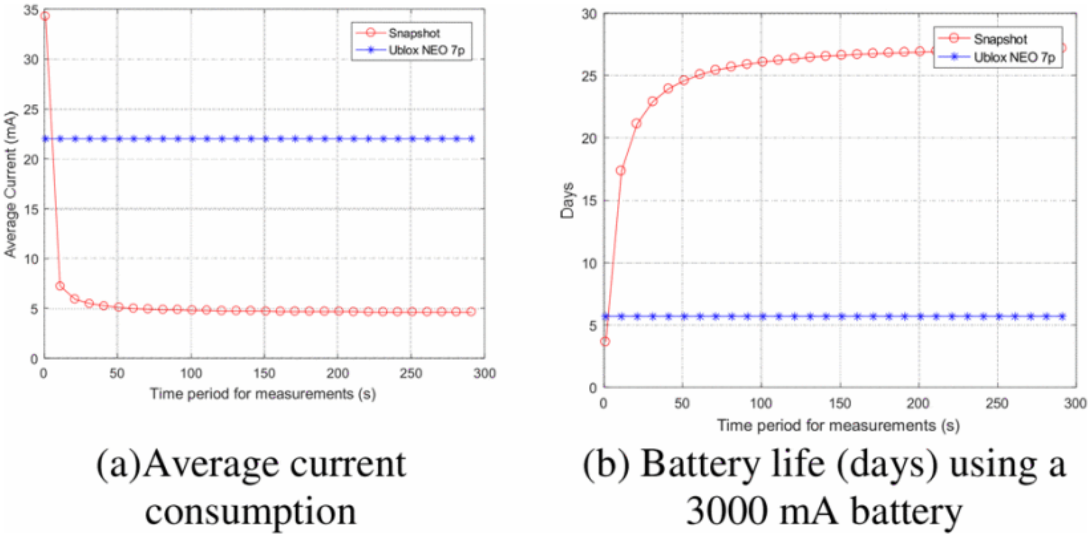

Figure 2.2: Dinh's[1] results showing improved battery life and expected current consumption with the proposed system.

Regarding IoT networks, it is expected for less power to be used as a result of the strict requirements for communication. One such example would be Cheong et al.'s[34] looking at the possibility of using LoRa class A and class C devices for up to 10 years. The conclusion there was that it was possible provided strict message sending requirements were met which included the payload size, spreading factor and transmission interval.

Another study by Domingo-Prieto et al.[35] looked specifically at how the message size would affect the power consumption, if at all. This was tested by using Huffman encoding for long messages and generally looking at the message lengths that were not encoded. It was concluded that the shorter the message, the smaller the power consumption, which led to a longer lifetime with a single battery charge.

2.4.1 Developing past work

Having considered the above work done by multiple authors, this report will aim to address a combination of factors that have not been fully addressed in the cited reports and papers.

Firstly, this investigation will look into combining the results of the work done by Domingo-Prieto et al.[35] regarding reducing the message size to obtain a lower power consumption. Furthermore, the work done by Choi et al.[28] will be built upon except for a fingerprinting algorithm for both LoRa and IEEE802.15.4 private networks.

Finally, the use of a four-node personal area network for both LoRa and IEEE802.15.4 as opposed to a single reference node as demonstrated by Al Mamun et al.[25]. This will be combined with a similar dynamic mapping technique as used by Farnham[21] with RSSI based distance estimation as opposed to AoA based distance estimation.

Chapter 3

Design

This chapter will detail how the equipment used for the evaluation was assembled as well as some of the reasoning behind the chosen components. It will also contain the requirements necessary to fulfil the aims of the experimentation process presented in Chapter 4. Finally, the cost breakdown and bill of materials for the main transceiver module will be presented.

3.1 Requirements

This section will outline the key user, functional and design requirements for the design of the experiment and its equipment. The verification and validation of this criterion will be presented in Section 3.4.

3.1.1 User Requirements

Table 3.1: This table details the user requirements that were used to realize the test equipment for this investigation.

UR01	**Module must be wireless**
Requirement	The transceiver module must be battery powered. The battery must be rechargeable.
Rational	Having the module battery powered allows it to be more mobile and able to be placed anywhere.

Refined by	UR01-FR01, UR01-FR02, UR01-FR03
Verification	Verified by inspection

UR02	**Module must be small**
Requirement	The transceiver module must be able to be held in one hand,
Rational	This allows the module to be moved and placed in any location and set up to run and evaluated.
Refined by	UR02-FR01
Verification	Verified by inspection

UR03	**The module must be able to communicate**
Requirement	The module must be able to send and receive data packets
Rational	In order to obtain an RSSI value a packet would need to be received from another transceiver.
Refined by	UR03-FR01, UR03-FR02, UR03-FR03
Verification	Verified by testing

UR04	**Device must be able to sleep**
Requirement	Low power modes must be available on all devices.
Rational	In order to allow the most power savings low power modes must be available and accessible.
Refined by	UR04-FR01, UR04-FR02, UR04-FR03
Verification	Verified by demonstration

UR05	**Module must allow interaction**
Requirement	The module should be able to allow the user to receive feedback of what it is doing at all points.
Rational	This will allow all information to be retrieved from the module.
Refined by	UR05-FR01, UR05-FR02
Verification	Verified by demonstration

UR06	**Module must be cheap**
Requirement	The components that make up the device must be as cheap as possible.
Rational	This is to ensure that the cheapest possible set-up is used and evaluated.

Refined by	UR06-FR01, UR06-FR02
Verification	Verified by inspection

3.1.2 Functional Requirements

Table 3.2: This table details all the functional requirements that were used to realize the test equipment for this investigation. They are based on the requirements that are listed in table 3.1.

UR01-FR01	**Battery compatible**
Requirement	The module must have a connector to allow a battery to be connected
Rational	This connector will allow simple powering of the module.
Verification	Verified by inspection

UR01-FR02	**Module must be able to hold a battery**
Requirement	A battery holder must be mountable on the module either on the front or on the back
Rational	This would allow the battery to be close to the module reducing losses as a result of cable length and to keep the module compact
Verification	Verified by inspection

UR01-FR03	**A battery must supply power**
Requirement	The battery must be able to deliver sufficient current and voltage.
Rational	This is to allow the entire device to be sufficiently powered and adequately able to supply the external power required.
Verification	Verified by demonstration

UR02-FR01	**Module must be handheld**
Requirement	The module must be small enough to fit in the palm of one had
Rational	This allows portability and placement in most packages.
Verification	Verified by demonstration

UR03-FR01	**Microcontroller must be able to communicate via SPI**

Requirement	The microcontroller must have at least 1 SPI bus.
Rational	In order to communicate with the radios an SPI capable device must be used.
Verification	Verified by demonstration

UR03-FR02	**Radio must be able to communicate via SPI**
Requirement	Radios must allow 2 way communication via at least 1 SPI bus.
Rational	In order to send or receive packets, the radio must be able to flag the microcontroller.
Verification	Verified by demonstration

UR03-FR03	**Radio must alert microcontroller of events**
Requirement	The radio must have an interrupt that is raised when specific events occur.
Rational	To allow efficient communication and power management, this feature is needed to only keep devices on when needed.
Verification	Verified by demonstration

UR04-FR01	**Microcontroller must be able to sleep**
Requirement	The microcontroller must be able to enter at least one sleep mode
Rational	This helps with the power usage of the devices.
Verification	Verified by demonstration

UR04-FR02	**Radio must be able to sleep**
Requirement	The radio must have at least one sleep mode.
Rational	This helps with the power usage of the devices.
Verification	Verified by demonstration

UR04-FR03	**Radio must be able to receive packets while sleeping**
Requirement	The radio must listen out for packets and wake up to receive them automatically
Rational	This helps with the power usage of the devices.
Verification	Verified by demonstration

UR05-FR01	**Module must give feedback to the user**

Requirement	The microcontroller must be able to communicate with the user about packet information and what it is doing.
Rational	This allows for the extraction of data from the system,
Verification	Verified by demonstration

UR05-FR02	**User must be able to select mode**
Requirement	The module must be able to select what mode a device will operate in
Rational	To allow diagnostics and specific data output.
Verification	Verified by demonstration

UR06-FR01	**A single module must use available components**
Requirement	A module must consist of common off the shelf components.
Rational	This would allow easy access and reproduction of the design.
Verification	Verified by inspection

UR06-FR02	**There must be a low cost - power usage**
Requirement	The module should be cheap and uses a little power as possible
Rational	This aligns with the goals of the investigation that need a device that is affordable and can last on a single battery charge for a long time.
Verification	Verified by inspection

3.1.3 Design Specifications

Table 3.3: The main Design Specifications for this experiment to be fully realized. These stem from the Functional Requirements stated in Table 3.2

Specification	**Name**	**Description**
UR01-FR01-R01	Power Supply 1	2200mAh, Lithium Ion Battery
UR01-FR03-R01	Power Supply 2	3.3V, 500mA Voltage Regulator
UR02-FR01-R01	Device Size	No more than 10cm x 10cm x 5cm
UR03-FR01-R01	Microcontroller 1	Must have at least 1 full duplex SPI bus, with mode 0
UR03-FR02-R01	Radio 1	Must have at least 1 full duplex SPI bus, with mode 0

UR03-FR03-R01	Microcontroller 2	Must have at least 1 GPIO pin capable of raising interrupts
UR04-FR01-R01	Microcontroller 3	Microcontroller must have a low power mode that uses less than 10% of the normal current consumption.
UR04-FR03-R01	Radio 2	Radio must have a low power mode using less than 10% of the normal current consumption
UR05-FR01-R01	Microcontroller 4	Microcontroller must have a UART interface to send debug information

3.2 Equipment selection and design

3.2.1 GPS

To obtain a location, a GPS device would be required for this investigation. With many options on the market such as the UBlox Lea 6T used by Dinh[1] in their investigation or other commercially available modules such RF Solutions' GPS-310FS[36]. Had either of these two been chosen, the project budget would have been exceeded, not allowing for proper evaluation.

Given the circumstances caused by the Covid-19 pandemic, the best option to use was the authors mobile phone, a Huawei Mate 20 Lite. Its on-board GPS system allows for the use of simple GPS and A-GPS through an application called "GPS Coordinates"[2]. Screenshots of the application are shown in Figure 3.1.

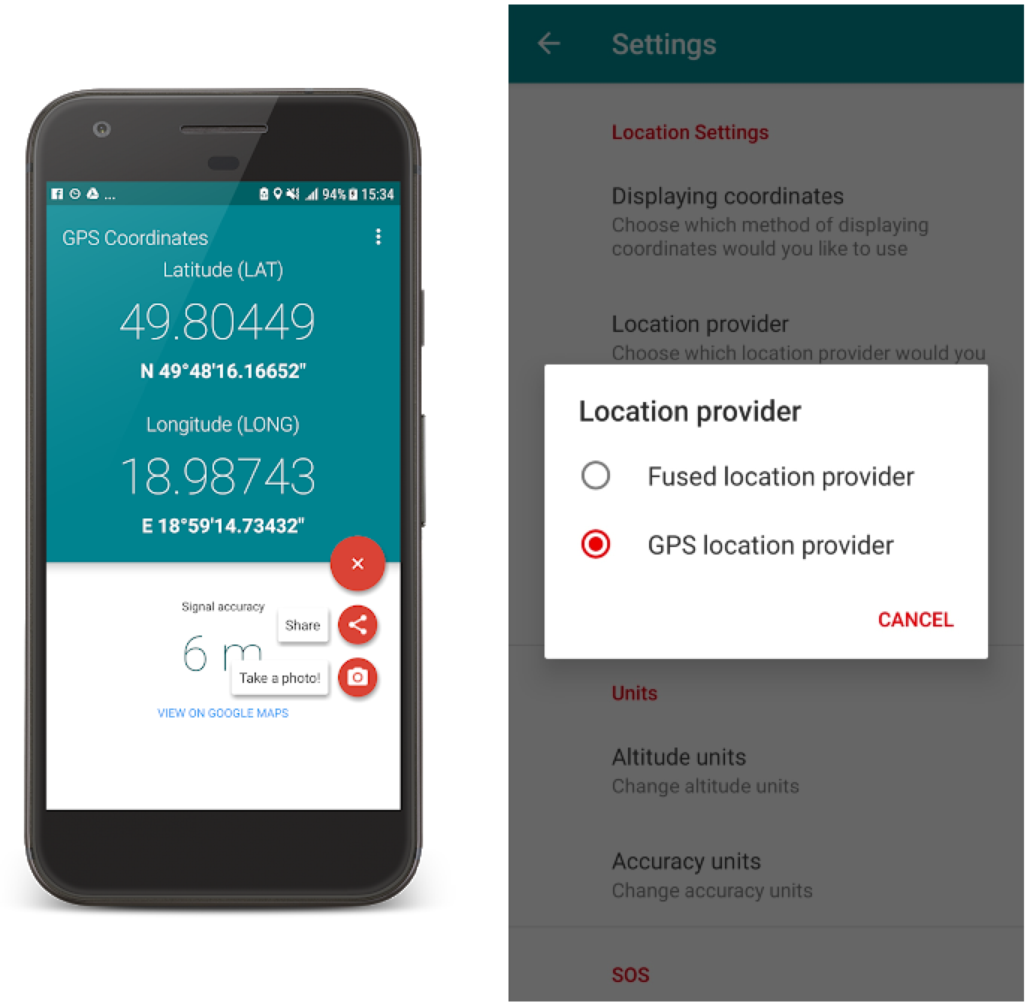

Figure 3.1: Screenshots of the GPS Coordinates application's user interface. The image on the right shows the options that allow the selection of GPS or A-GPS. The image on the left is obtained from the Google Play Store[2]

This application is well suited for this task as it not only shows the coordinates but it also shows the accuracy in meters of the measurement. The only problem will be obtaining the power consumption of this application.

3.2.2 LPWANs

For the sake of this study, the below network stacks were considered for use[37]:

Table 3.4: Comparison of LPWAN technologies that are available for use. (Part 1)

	BLE	**Zigbee & IEEE802.15.4**	**LoRa**	**IEEE802.11ah**
Bandwidth (MHz)	2	0.2-1.25	0.125	1 - 16
Range (m)	100	100	15000	1000
Frequency (GHz)	2.4	2.4	0.433, 0.868	2.4, 5
Operators	Personal	Personal	Public	Personal
Availability	Yes	Yes	Yes	No
Data Rate (kbps)	1000	250	11	150

Table 3.5: Comparison of LPWAN technologies that are available for use. (Part 2)

	NB-IOT	**Weightless**[38]	**6LoWPAN**
Bandwidth (MHz)	0.18	6	2 - 5
Range (m)	20000	2000	100
Frequency (GHz)	8, 9	0.433, 0.868	2.4, 5
Operators	Private	Private	Private
Availability	No	Yes	Yes
Data Rate (kbps)	26	0.625-100	250

For this investigation, it was decided that one long range option and one short range option must be used. Long range is defined by the range of the possible network being greater than 1000m. Beyond this, the operational rules in South Africa and the availability of support infrastructure are considered alongside the cost of devices needed for this implementation.

The local carrier that supported NB-IoT had not yet rolled out to Cape Town and was unavailable when contacted. This left only LoRa as the sole long range option available. Regarding the short range networks, due to the vast work done with BLE, the lack of IEEE802.11ah devices on the market available and the high cost of Weightless and 6LoWPAN devices, Zigbee and IEEE802.15.4 devices were the last option on the table.

The modules chosen for this were going to be capable of operating in both modes, but since the extra functionality of Zigbee was not going to be needed for the investigations, IEEE802.15.4 was chosen.

3.2.3 IEEE802.15.4

When it came to selecting the XBee modules, there was little issue regarding RF bands that could be used as 2.4GHz is within the International Scientific and Medical band which is free to use. The options that were available were Microchip's MRF24J40MA[39] and Digi International's XBee PRO S2C[3]. These two boasted similar specifications, but the price difference between the two was stark with prices at R260 and R650 per device, respectively. The MRF24J40MA has a PCB antenna as opposed to the XBee PRO S2C which has a dipole antenna.

Due to the number of devices needed to achieve localisation, it was concluded that the MRF24J40MA would be selected. Figure 3.2 shows the module and its pin-out. This module communicates via SPI and has a sleep mode available as well as hardware interrupts that are used to indicate received or transmitted packets.

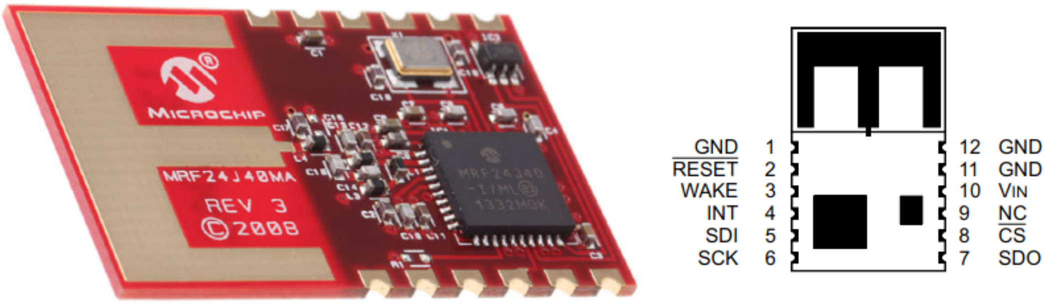

Figure 3.2: The MRF24J40 manufactured by Microchip alongside its pin-out diagram. The module image is taken from RS Components and the pin-out from the modules datasheet.[3]

3.2.4 LoRa

The selection of LoRa modules was first determined by the radio frequency bands that were free to use in South Africa according to the governing body ICASA. This limited the options to 433MHz and 868MHz boards. The two options were the Ra-01 LoRa Module made by AI Thinker which operates at 433MHz[40] and the RFM95W[4] which operates at 868MHz. These were the cheapest options available for their ranges with prices of R160 and R390 per module, respectively.

The RFM95W was chosen because at the time of purchase, the Ra-01 was not in stock with the supplier. It only became available at a later stage of the investigation. Since there was no option of inter-usability, all devices used were the RFM95W. Figure 3.3 shows the module itself and its pin-out diagram. This module uses SPI to communicate with a master device and features an external interrupt via its DIO0 pin. It also has an external antenna pin on the module. It is also based on the SX1276 made by Semtech.

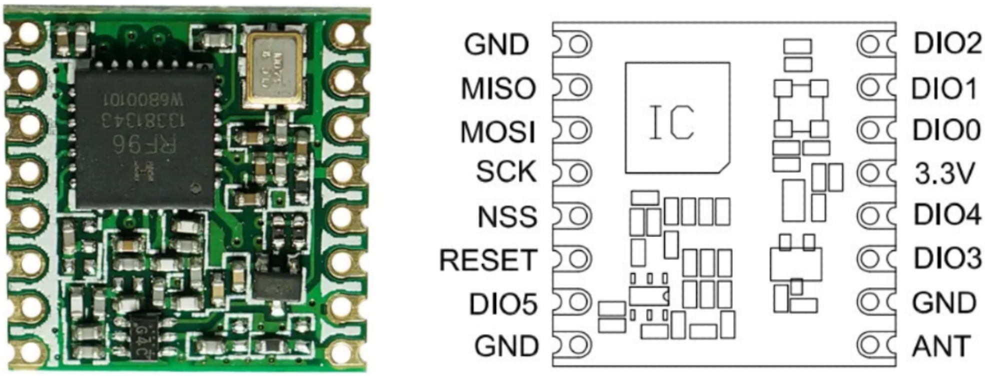

Figure 3.3: The RFM95W manufactured by Hope Electronics alongside its pin-out diagram. The module image is taken from RS Components and the pin-out from the modules datasheet.[4]

To use the RFM95W, a breakout board was needed and Figure 3.4 shows which pins were essential for operation and were extended out.

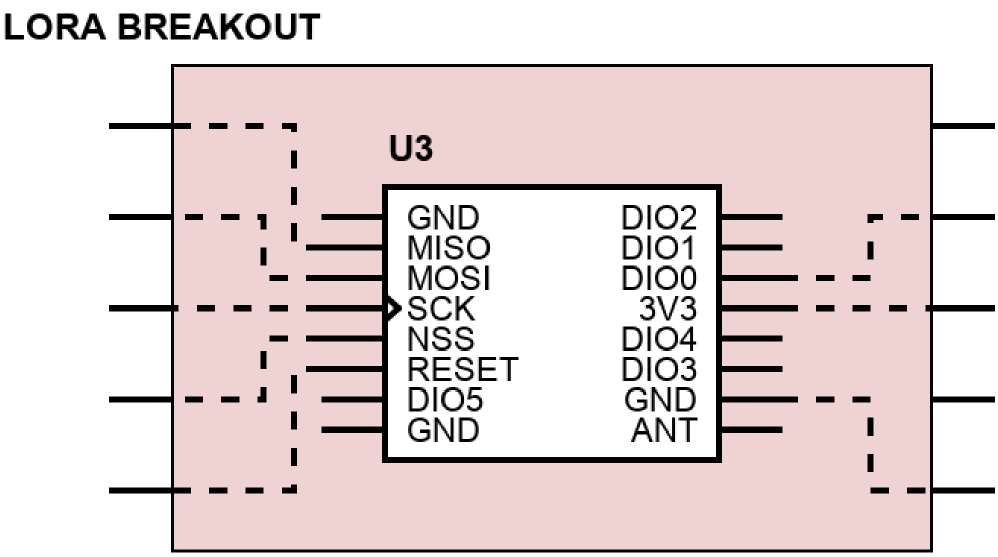

Figure 3.4: The breakout designed to interface with the RFM95W module.

3.2.5 Microcontrollers

To integrate well with the chosen radio modules, it was important to choose a microcontroller that had SPI connectivity as well as low power modes. Due to the low computational power needed for the investigation, any microcontroller was suitable so long as it had the SPI pin-out as well as six available GPIO pins. The chosen module had to also be small and compact to keep the form factor of the end devices small.

The options that were looked at are detailed in the table 3.6.

Table 3.6: Comparison of the possible microcontrollers that could be used. Details obtained from the respective processor IC datasheets.
* The development board does not break out the necessary pins.

Microcontroller Board	Nucleo F031K6	DM164141	PIC16F18446 Curiosity Nano
Processor IC	STM32F031K6T6	PIC16F18345	PIC16F18446
Manufacturer	ST Microelectronics	Microchip	Microchip
Low Power Modes	3	5	5
GPIO	22	18	18
SPI Connectivity	Yes	Yes*	Yes
Word size (bits)	32	8	8
Voltage (V)	3.3	3.3	3.3
Speed (MHz)	24	24	32
Cost (ZAR)	210	200	250

Due to not only the cost and available low power options, the Nucleo-F031K6 Nucleo-32 Development Board was chosen. Its small form factor and accessible power measurement pins, this development board was ideal to be used in this investigation.

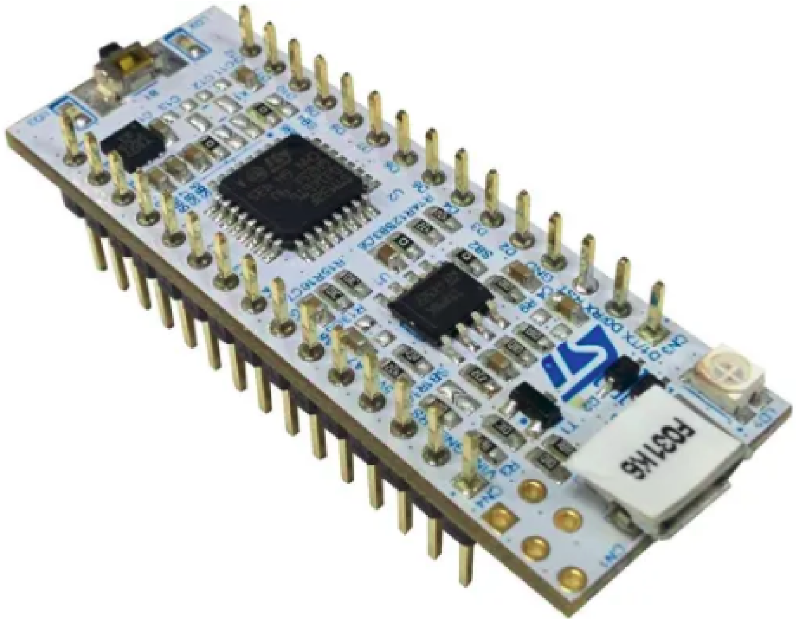

Figure 3.5: The Nucleo-F031K6 development board. Image taken from RS Components.

3.3 Final Design

This section will detail the final hardware design that has been proposed for the transmitter and receiver. Due to the budget, certain changes had to be made to some of the components such as the receiver that was used to obtain location data. Furthermore, not all the components used needed to be purchased as some of them were already owned by the author. This section will also outline the firmware that was used for the experimentation software as well as an algorithm which may be used in a deployment.

3.3.1 Hardware

Transceiver

The transceiver was designed with the goal of using a singe unit to carry both the RFM95W and the MRF24J40MA and operate both at the same time. This led to the schematic shown in Figure 3.6. This allowed the interrupts to be sent to the device as well as a "hard" reset through the microcontroller. This schematic later incorporates a 2200mAH Lithium Ion Battery to power the module at the Vin pins in Figure 3.7. Because the Nucleo board has an on-board voltage regulator, there is no need for an external regulator.

The 3.3V pin on the Nucleo board is used to supply the radios with power as it can output up to 500mA of current to the radios. This is more than the expected draw from running the radios at their peak transmission draw that is stated in their datasheets(the highest is the RFM95W transmission at maximum power and microcontroller running at maximum speed).

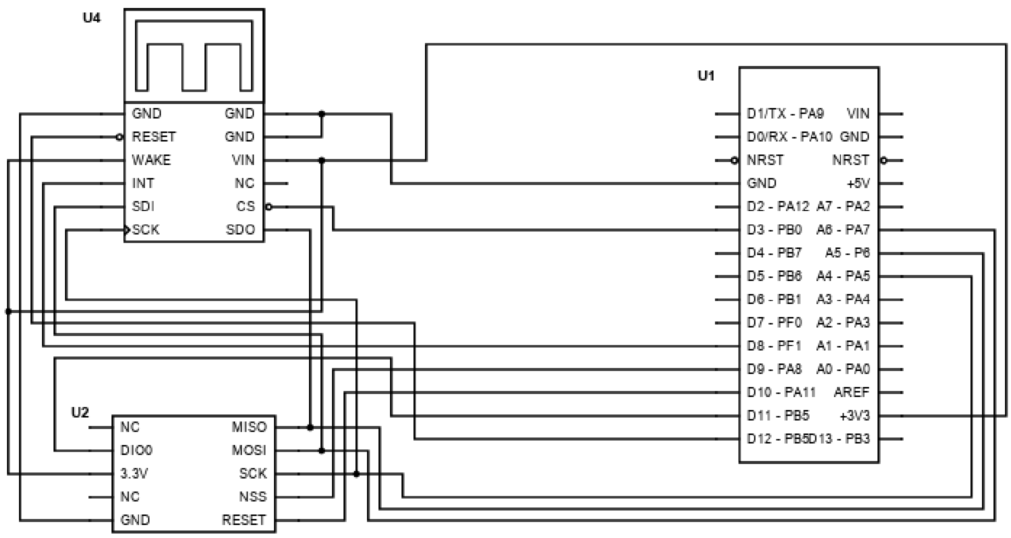

Figure 3.6: This is the main schematic that shows how the radios are connected to the microcontroller. For successful operation.

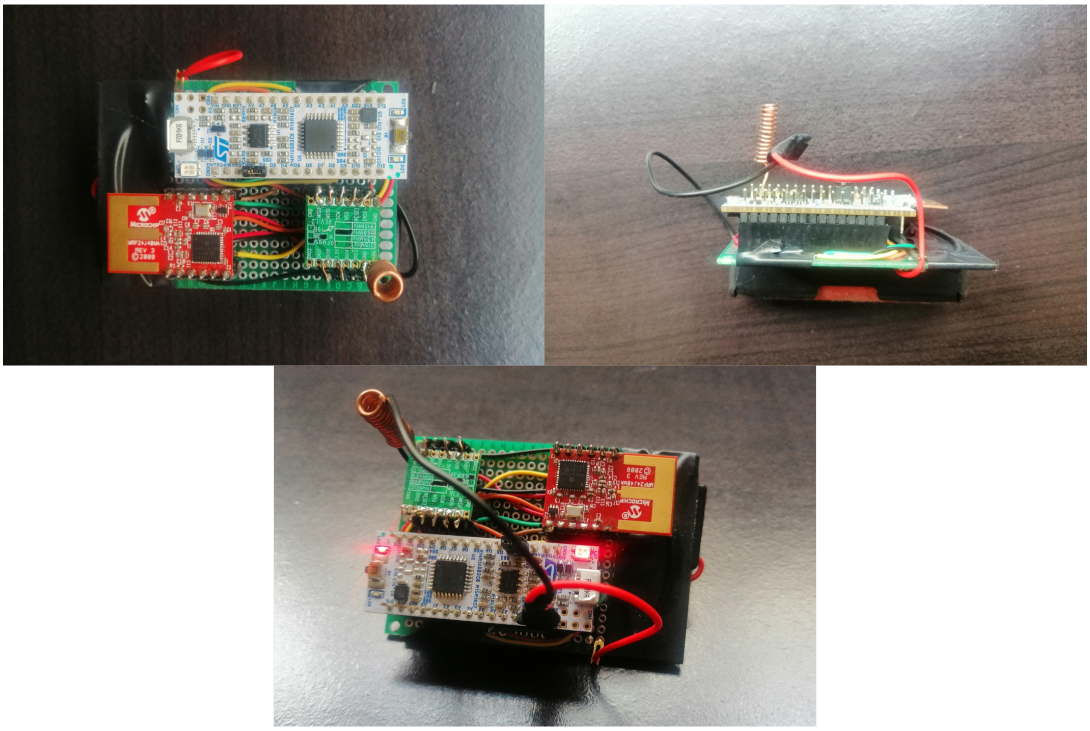

Figure 3.7: The transmitter built for the investigation. The images show a top down view(top left), a side profile(top right) and an angled view of the device in operation(bottom).

MRF24J40 Issues

It should be noted that there was an issue while using the MRF24J40 in the testing phase of this investigation, it was found that the power being supplied to the module was not sufficient to transmit a packet after the LoRa module had sent its packet. A new receiver was used and is shown in Appendix A.3.

Evaluation Receiver

As a result of a lack of Nucleo-F031K6 boards and the budget being exhausted, it was decided to use an already owned development board based on the STM32F051C6. This development board features a LCD, four buttons, multiple LED's connected to various pins on the microcontroller and an on-board debugger. While this will not be any accurate representation of the power measurements to be done, the functionality of the device is similar to that of the Nucleo board. More details of this receiver can be found in Appendix A.2. The important details, however, are that it also operates on 3.3V and has the necessary SPI communication pin-out and it also meets the minimum available

GPIO requirements.

This board will carry an extra radio board that will house a MRF24J40MA and a RFM95W. This radio board is shown in Figure 3.8. The two are connected by means of an umbilical that attaches to some of the pins on the development board. The entire unit is powered by a power bank that delivers 5V to the main power supply that is regulated to 3.3V by the microcontroller board.

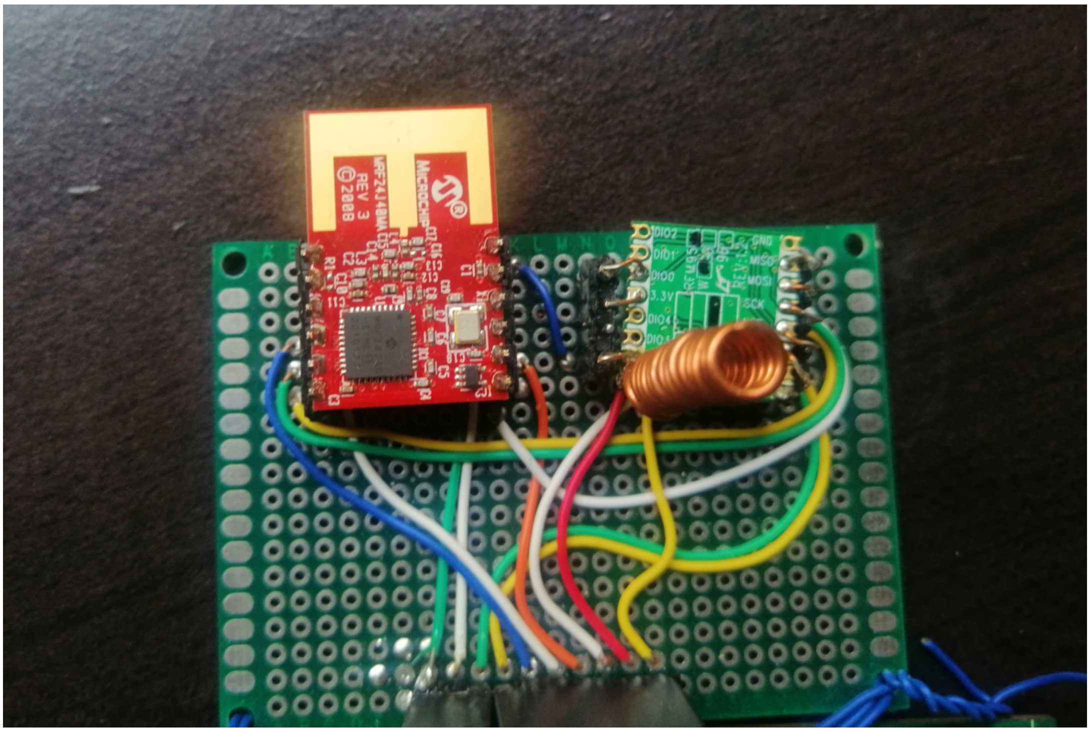

Figure 3.8: The extension board that holds the radios. The umbilical can be seen at the bottom of the image.

3.3.2 Software

In order to program the Nucleo-F031K6 board, an on board debugger was used alongside the STM32CubeIDE, made by ST Microelectronics(STM), was used. The inbuilt STM Hardware Abstraction Layer (HAL) was also used to simplify the development of the firmware. All of the program code used if open source and covered by the MIT License. This software may be found in an online repository linked to in Appendix A.1.

To further speed up the development time, libraries written by Belyalov[41] and Palsson[42] for the RFM95W and MRF24J40 respectively were used with minor modifications to suit this implementation. These were written in C and incorporated with the STM HAL.

Transceiver

The transceiver unit is the base unit required for operation. For the purpose of this evaluation, it will incorporate both the MRF24J40MA as well as the RFM95. This means that the firmware needs to be able to swap between transmitting or receiving LoRa packets and IEEE802.15.4 packets.

For the evaluation, a set of devices is programmed as transmitters and one will be set as a receiver. The transmitters remain on for the entire duration of the operation, sending a LoRa and IEEE802.15.4 packet every second. This message is as small as possible to reduce power usage as shown by Domingo-Prieto et al.'s work that supported this decision. The content of the message is the tower ID, in this case, it is okay to use a single byte that denotes this. Figure 3.9 shows a flowchart of how this will all work. It is important to note that neither of these protocols require an acknowledgement message to be sent back to them. The proposed program for deployment would follow the flowchart shown in Appendix A.2.

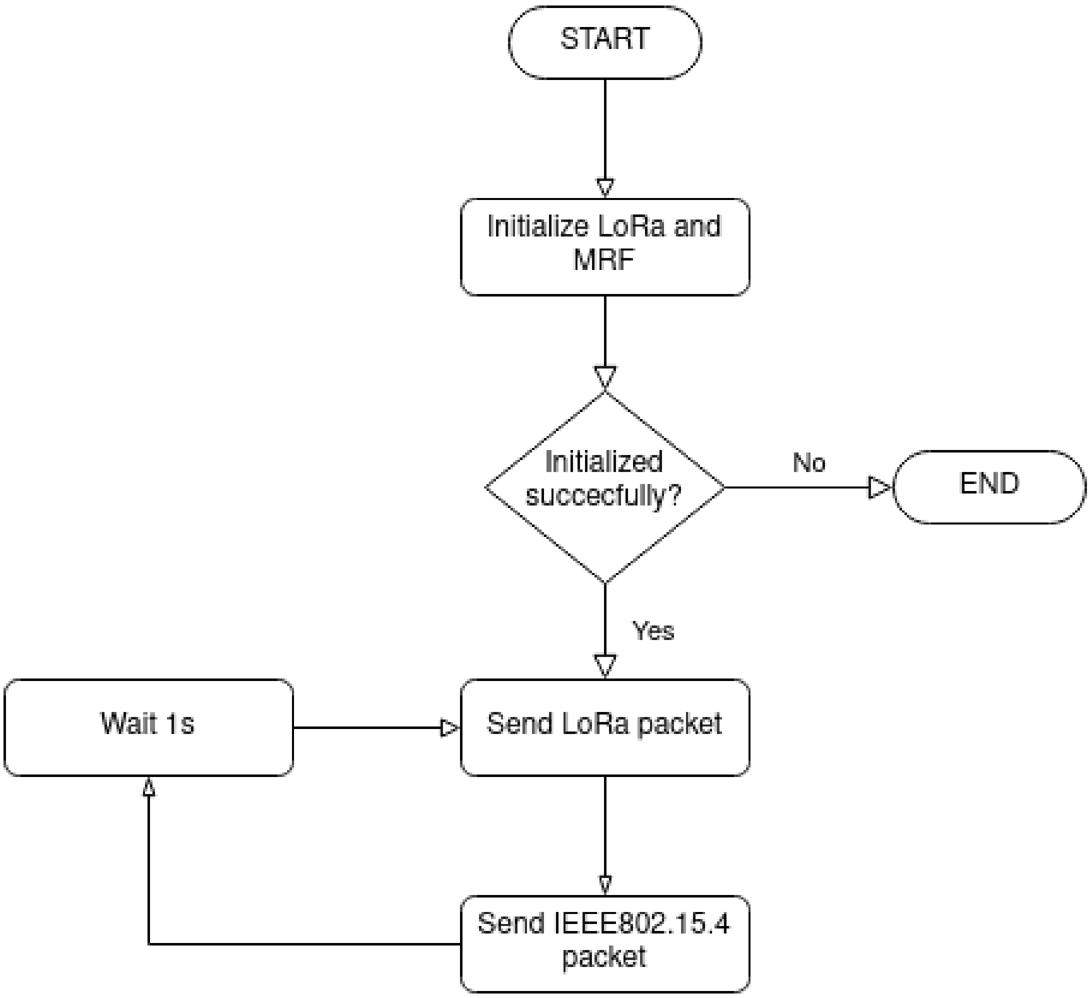

Figure 3.9: A flowchart showing the transmitter routine for the localisation tests.

Evaluation Receiver

As a result of using a different development board for the reception in this investigation, the firmware used could be different and be more extensible. The advantage of the STM HAL is that it allows portability between STM microcontrollers of the same family. This means that the same libraries and commands could be used between the STM32F031K6 and the STM32F051C6.

Due to the fact that a LCD was available to display information, an extra library was needed to run this written by Verrinder et al.[43]. The flowchart for this is found in Figure 3.10.

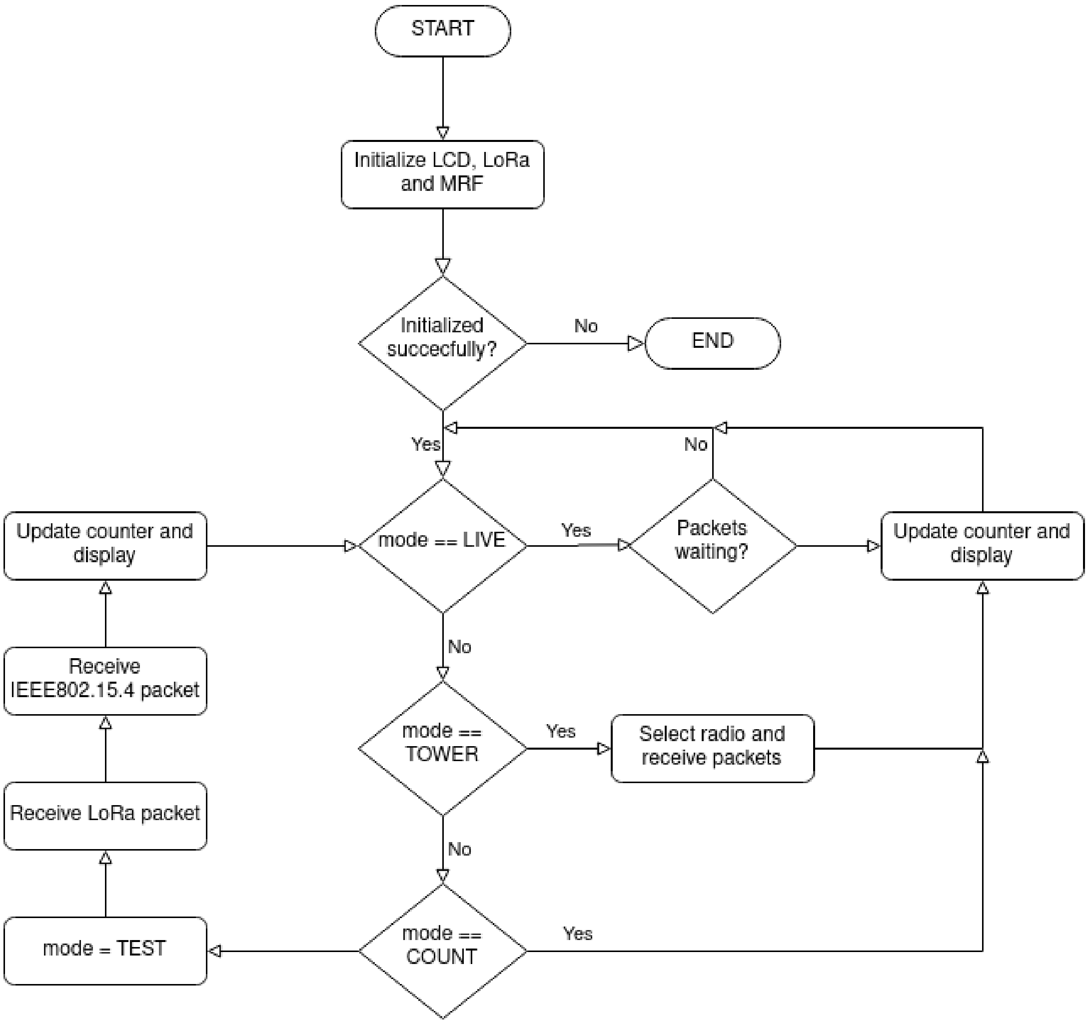

Figure 3.10: A flowchart showing the receiver routine for the localisation tests.

The modes available for reception as well as display are shown in Figure 3.11.

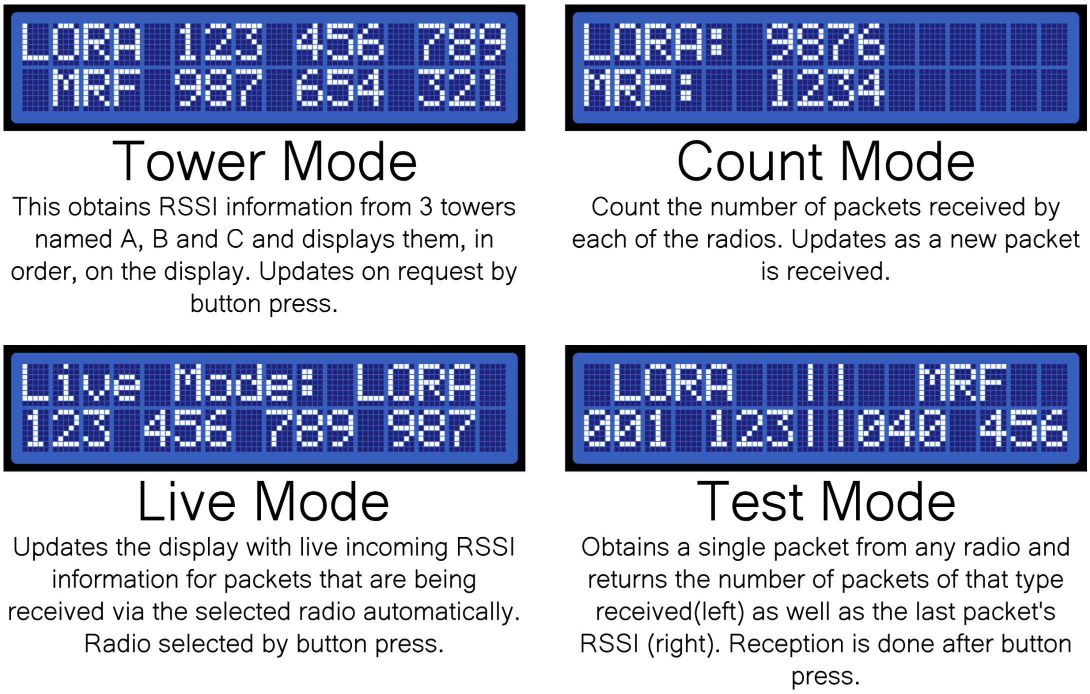

Figure 3.11: A diagram showing and explaining available modes on the receiver module. The example display is also shown.

3.3.3 Bill of materials and costs

The cost of a single transceiver module that will be used for the investigation is detailed in Table 3.7.

Table 3.7: Bill of material and cost of a single receiver unit used for this investigation. *Items were already available and did not need to be purchased with the project budget.

Item	**Price per item**	**Quantity**	**Cost**
Prototype board*	R15.00	1	R15.00
40 x 1 Female headers*	R6.90	2	R13.80
40 x 1 Male headers*	R4.43	1	R4.43
MRF24J40MA	R260.00	1	R260.00
RFM95W	R390.00	1	R390.00
Nucleo-F031K6	R210.00	1	R210.00
Lithium Ion Battery*	R95.00	1	R95.00
Li-Ion Battery Holder*	R14.00	1	R14.00
		Total	**R1,002.23**

All of the wiring costs and solder costs are no included as they were very small had no effect on the final cost.

The total cost of the investigation is shown in Table 3.8. This covers all the costs excluding wiring and solder costs.

Table 3.8: Total cost and bill of materials used in this investigation.

Item	**Price per item**	**Quantity**	**Cost**
Prototype board	R15.00	1	R15.00
40 x 1 Female headers	R6.90	8	R55.20
40 x 1 Male headers	R4.43	6	R26.58
MRF24J40MA	R260.00	4	R1,040.00
RFM95W	R390.00	4	R1,560.00
Nucleo-F031K6	R210.00	3	R630.00
Lithium Ion Battery	R95.00	3	R285.00
Li-Ion Battery Holder	R14.00	3	R42.00
UCT Development Board	R500.00	1	R500.00
Mini Power Bank (2600mAh)	R92.00	1	R92.00
		Total	**R4,245.78**

3.4 Design validation

In order to validate that the proposed design was fit for the evaluation that was to be completed.

Table 3.9: Results from the design verification tests that validated devices that would be used for the assessment.
*This success of this test was not reliable. Some of the packets were not received.

Validation Test	**Name**	**Description**	**Result**
1	Size	Pass if size <10cm x 10cm x 5cm.	PASS
2	IEEE802.15.4 transmission/reception	Send an IEEE802.15.4 packet and receive another using two radios. Pass if receiver gets a packet.	PASS

3	LoRa transmission/reception	Send an LoRa packet and receive another using two radios. Pass if receiver gets a packet.	PASS
4	Microcontroller Communication	Send message via UART to the host computer. Pass if message is received.	PASS
5	Power Supply	Power external radios with 3.3V radios. Pass if transmission of both radio packets is successful.	FAIL*

Chapter 4

Testing Methodology

This chapter will look to propose the relevant testing protocol to be followed for the investigation. It will also outline the importance of the test

4.1 Accuracy and Precision Testing

To fully evaluate the performance of each of the networks, there is a need for a rigid testing regiment that will fully evaluate the key metrics that are under investigation. For this, four groups of tests were to be conducted. These groups are accuracy, precision, power consumption and range. These will be further outlined in order of priority below, but first mapping of the environment must be done. The same data sets will be used for accuracy and precision results. Figure 4.1 will further illustrate the definition of precision (Δ) and accuracy(τ).

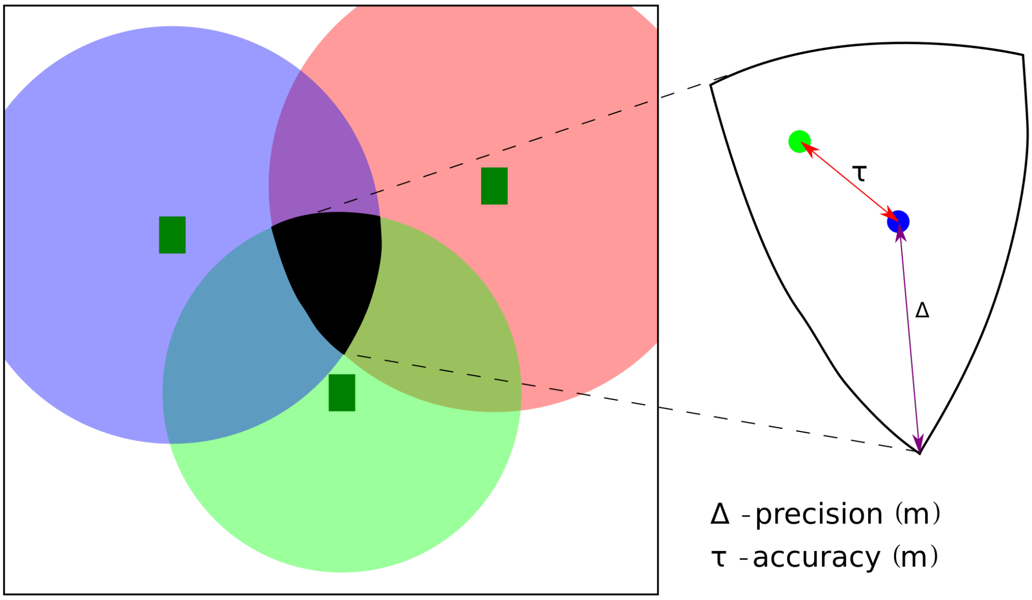

Figure 4.1: An illustration of the definition of precision and accuracy that will be used for this report. The green rectangles represent the beacons/base stations while the circles round them indicate the proximity of the device being located. To the right is the extracted overlapping area. The blue dot represents the estimated location while the green dot shows the true location.

4.1.1 Range Mapping

Before any testing is done, there is need for the environment under which the testing will be done to be mapped with different distances from the radios. **NB**: The RSSI value is measured as an unsigned 8-bit integer. This means that the maximum RSSI value would be 255 and the lowest being 0.

Outdoors

For this a single receiving radio will be moved a known distance away from a transmitter radio. Measurements of the RSSI will be taken from 1m to 5m at 1m intervals, then from 10m to 100m in intervals of 10m. From then onward measurements will be taken at 50m intervals till 400m. Below is the table in which the data will be collected with an example measurement. These will be done with both the receiver and transmitter being at the same height.

This test will be conducted in a field with a total 34 820m^2. It will allow for an environment that would be similar in size to a medium-sized factory and would also show the radios performing in a best case scenario with less interference and reflections.

Figure 4.2: Satellite image of the field to be used for testing the radios and their capabilities. Map obtained from Zoom Earth

Indoors

For the indoor mapping, measurements will be taken at intervals of 1m through the path with the most interference. This will be done with as many doors closed so as to create a worst case measurement. For this an single receiver and transmitter pair will be used.

For the indoor mapping, a house (with floor plan in Figure 4.3) with a total of 105m^2 will be used. This will be adequate enough to demonstrate how effective each of the networks would work in smaller environments that have more reflections and interference.

Figure 4.3: Floor plan of the indoor space that will be used for testing the network stacks. All walls are brick walls of 15cm.

Table 4.1: Example table for dynamic mapping

Distance (m)	$\mathbf{RSSI}_1$	$\mathbf{RSSI}_2$	$\mathbf{RSSI}_3$	$\mathbf{RSSI}_{average}$
10	*234*	*230*	*232*	*232*

From this table data, further points will be made using linear algebra to fill the gaps and allow for RSSI values to be made. These data points will be used to make a reference table for the locating device. This data will also be displayed on a graph to better show the relationship between RSSI and distance.

4.1.2 Accuracy

Accuracy in this experiment is defined as how close to correct the measured value is. When a location is requested and obtained, what would the euclidean distance from the estimated point be to the actual point in space. This is best illustrated as the distance τ in Figure 4.1. Below is the table that will show some localisation data.

Table 4.2: Example table for accuracy tests

Location	**RSSI$_A$**	**RSSI$_B$**	**RSSI$_C$**	**True Position (x,y)**	**Final Position (x,y)**	**Error (m)**
1	*234*	*230*	*232*	*4,5*	*5,5*	*1*

This test is conducted by taking an average RSSI value from a single tower that transmits 3 packets and obtaining a distance measurement from the dynamic map. A location is then

4.1.3 Precision

The definition of precision for these measurements will be the largest possible distance of estimation given a location. This is best described as the distance Δ in Figure 4.1. Table 4.3 shows an example of how the data will be compiled to obtain this metric.

Table 4.3: Example table for precision tests

Location	**RSSI$_A$**	**RSSI$_B$**	**RSSI$_C$**	**Obtained Position (x,y)**	**Furthest Overlapping Point (x,y)**	Δ
1	*234*	*230*	*232*	*4,5*	*6,5*	*2*

The precision will be represented by a circle of radius Δ around the obtained position. The RSSI values collected from each of the beacons (A, B and C) will be the same as those obtained from the accuracy tests.

4.1.4 Power consumption

By measuring the current consumed by a single radio and the microcontroller over known cycles of transmission and reception, the overall power consumption of a receiver and transmitter can be obtained. This is normally done using a multi-meter in it's ammeter mode however due to a lack of available equipment, the STM32CubeIDE's power consumption calculator will be used. Table 4.4 will be used to collect the data obtained. All the radio power information will come from their respective datasheets according to their modes of operation.

Table 4.4: Example table for power consumption tests

Radio	**Mode**	**I_{radio} (mA)**	**$I_{\mu C}$ (mA)**	**Time (ms)**	**Power (mW)**
LoRa	*Reception*	*59*	*50*	*200*	*359*

4.1.5 Cost

In order to asses the cost of running these two networks, the overall architecture cost for a single receiver will be put to the test. Because the cost of a satellite launch is significantly higher than the project budget, only the cost of a single receiver will be put to question and compared. The example table for this is Table 4.5.

Table 4.5: Example table for cost analysis

Radio	**$Cost_{\mu C}$ (ZAR)**	**$Cost_{radio}$ (ZAR)**	**$Cost_{extra}$ (ZAR)**	**Total (ZAR)**
LoRa	*210.00*	*390.00*	*142.23*	*742.23*

4.1.6 Final Comparison

When coming to a conclusion on the effectiveness of each of the localisation networks, Table 4.6 will be used to allow a broad over view of the metrics that were key in the investigation. These metrics will also include the cost and an expected lifetime based on the use of a 2200mAH Lithium-Ion battery that nominally operates at 3.7V. The accuracy and precision will be average values calculated from the create a special broad test case test.

Table 4.6: Example table for final comparison

Network Stack	**Precision (m)**	**Accuracy (m)**	**$Cost_{transmitter}$ (ZAR)**	**$Cost_{receiver}$ (ZAR)**	**Expected Lifetime (years)**
802.15.4	*3*	*10*	*340*	*340*	*2*

4.2 Testing procedure

Tests in Table 4.7 will be used to obtain the necessary results for this investigation. The following tests will be run indoors and outdoors:

1. using the 802.15.4 protocol (X)
2. using the LoRa protocol(L)

Table 4.7: The tests that will be done to obtain the results for comparison.

Test Number	**Name**	**Description**
1	RSSI sensitivity	Finding out what the minimum distance is to have a change in RSSI
2	RSSI Range Acquisition	Finding out what RSSI values map out to different distances
3	Loss of signal	Discovering what the maximum distance that a packet can be sent
4	Localisation	Obtaining a location from the devices.
5	Material sensitivity	Using cardboard, wood, paper and a wall as an obstruction to see how the RSSI varies

Chapter 5

Results

The following are the results obtained from the various tests that were conducted as described in Chapter 4. These will be used to inform a discussion and conclusion for this investigation.

5.1 Tests Conducted

Based on Table 4.7, the following tests were run as shown in in Table 5.1.

Table 5.1: A compiled table of all the test that were run to obtain the necessary data for this investigation.
* Result is not admissible because the correct infrastructure was not available for this test.

Test	**Date Completed**	**Results Acceptable? (Y/N)**
L1	10-Nov-20	Y
L2	9-Nov-20	Y
L3	9-Nov-20	N
L4	9-Nov-20	Y
L5	9-Nov-20	Y
X1	10-Nov-20	Y
X2	11-Nov-20	Y
X3	11-Nov-20	Y
X4	11-Nov-20	N*
X5	10-Nov-20	Y

5.2 Power Analysis

Having followed the procedure described in Section 4.1.4, the following results were obtained. For further comparison, a copy of Table 5.2 is found in Appendix A.5 with details on the power consumption of the UBlox Neo-6M GPS receiver.

Table 5.2: Results based on datasheet values on the power consumption of the individual modules.

Radio	Mode	I_{radio} (mA)	$I_{\mu C}$ (mA)	Time (ms)	Power (mW)
LoRa	Reception	12.1	10.5	10	246.1
	Transmission	120	10.5	10	1421.1
	Sleep	0.0015	5.9	1000	64.3
IEEE802.15.4	Reception	19	10.5	10	321.3
	Transmission	23	10.5	10	364.8
	Sleep	0.002	5.9	1000	64.3

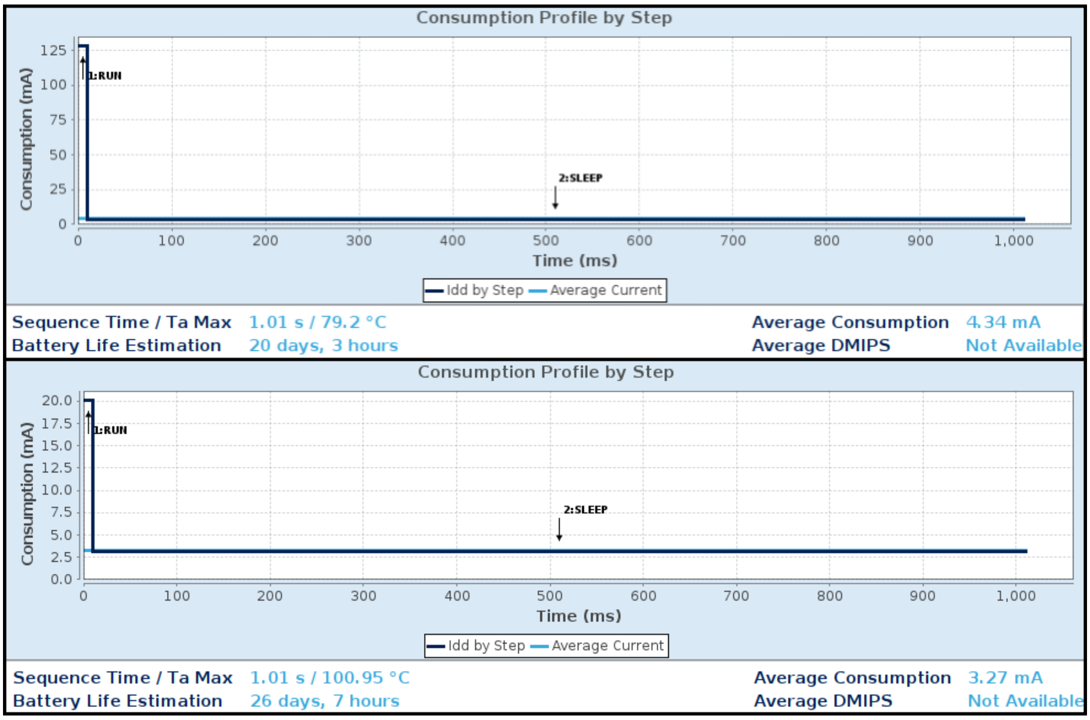

Figure 5.1: Obtained power consumption results of the LoRa radio using a 10μs transmit(top) or reception(bottom) and 1s sleep cycle running on a 2200mAh battery. Calculated by STMCubeIDE's Power Consumption Calculator.

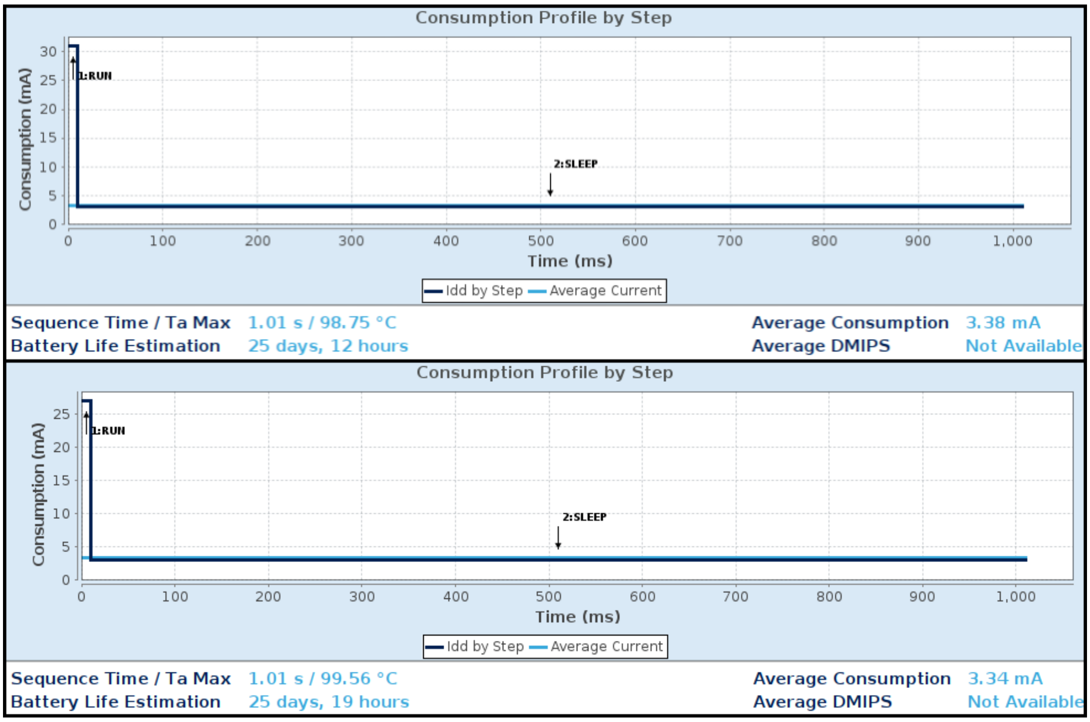

Figure 5.2: Obtained power consumption results of the MRF radio using a 10μs transmit(top) or reception(bottom) and 1s sleep cycle running on a 2200mAh battery. Calculated by STMCubeIDE's Power Consumption Calculator.

5.3 Cost Analysis

By using the prices listed in the bill of materials in Section 3.8, single receiver prices were compiled and put together and shown in Table 5.3. Appendix A.6 will have a table showing these prices and those of the UBlox Neo-6M GPS receiver.

Table 5.3: Results of the cost based on the listed prices in the bill of materials.

Radio	**Cost$_{\mu C}$ (ZAR)**	**Cost$_{radio}$ (ZAR)**	**Cost$_{extra}$ (ZAR)**	**Total (ZAR)**
LoRa	210.00	390.00	142.23	742.23
IEEE802.15.4	210.00	260.00	142.23	612.23

5.4 Range Tests

The full results table obtained from this test can be found in Appendix A.7. Table 5.4 will show the final ave raged RSSI values and their associated distanced as far as the field would allow. Figure 5.3 shows this profile more clearly for tests done with the RFM95W radios.

Table 5.4: Summary of the range tests conducted for the LoRa radio outdoors.

Distance (m)	0	1	2	3	4	5	20	40	60	80	100
$\mathbf{RSSI}_{average}$	253	244	241	193	191	189	183	176	176	173	168

Distance (m)	120	140	160	180	200	250	300	350	400
$\mathbf{RSSI}_{average}$	167	167	164	160	162	158	164	157	148

Table 5.5: Summary of the range tests conducted for the IEEE802.15.4 radio indoors.

Distance (m)	0	1	2	3	4	5	6	7	8	9
$\mathbf{RSSI}_{average}$	255	168	151	131	118	90	82	79	74	58

Distance (m)	10	11	12
$\mathbf{RSSI}_{average}$	56	49	36

Table 5.6: Summary of the range tests conducted for the LoRa radio indoors.

Distance (m)	0	1	2	3	4	5	6	7	8	9
$\mathbf{RSSI}_{average}$	255	241	192	181	175	165	155	140	125	110

Distance (m)	10	11	12
$\mathbf{RSSI}_{average}$	100	95	90

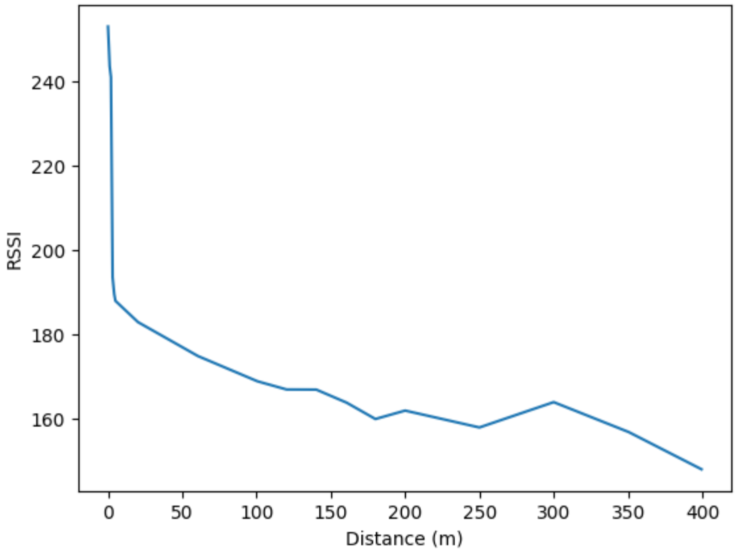

Figure 5.3: A graph showing the variation of RSSI with distance from the results obtained for LoRa outdoors.

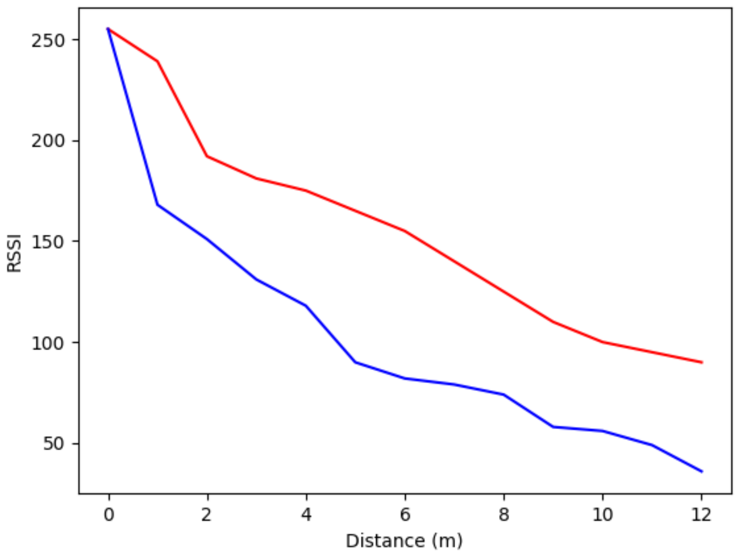

Figure 5.4: A graph showing the variation of RSSI with distance from the results obtained for IEEE802.15.4(blue) and LoRa(red) indoors.

5.4.1 Material Tests

In order to best understand the RSSI loss characteristics, different materials were used to enclose a transmitter and the obtained RSSI was measured. These results are shown in

Table 5.7 and Table 5.8 for LoRa and IEEE802.15.4 respectively. Figure 5.5 summarises these findings in a single graph.

Table 5.7: Results for the LoRa RSSI loss as a result of different material barriers.

	Distance (m)			
Material	**0**	**1**	**2**	**3**
Wood	201	191	187	183
Cardboard	215	200	191	186
Plastic	213	200	196	192
Brick	246	202	195	190

Table 5.8: Results for the IEEE802.15.4 RSSI loss as a result of different material barriers.

	Distance (m)			
Material	**0**	**1**	**2**	**3**
Wood	255	150	125	122
Cardboard	255	160	130	90
Plastic	255	129	70	105
Brick	155	129	75	82

Alongside this, the sensitivity (minimum distance to RSSI change from the maximum value) was obtained. For LoRa this distance was 7cm while for IEEE802.15.4, this distance was found to be 13cm. The maximum possible distance was only found for MRF24J40 receiver indoors as 17m.

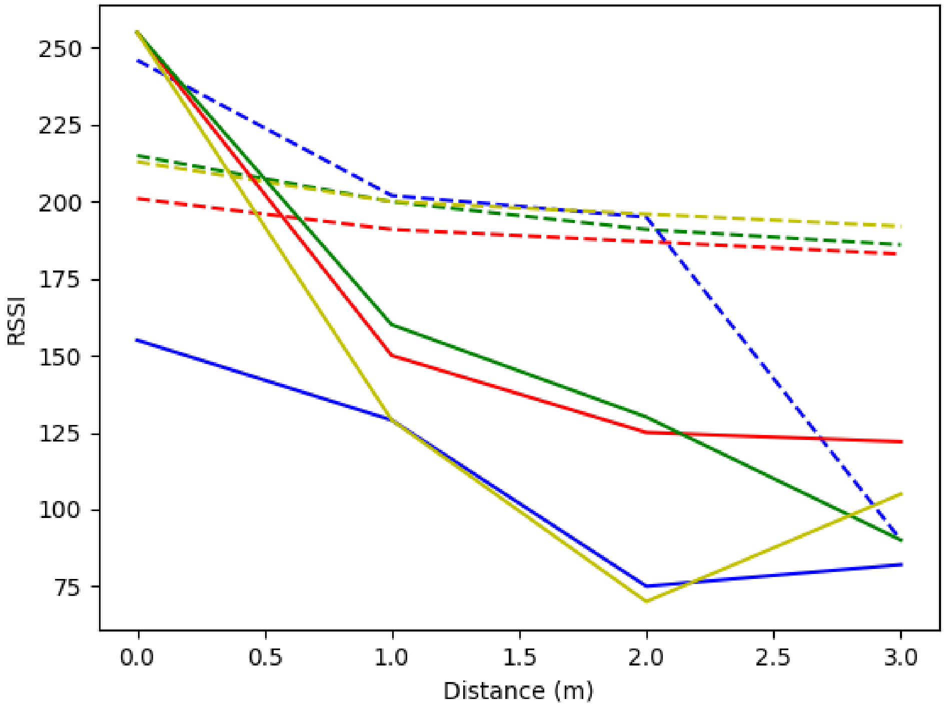

Figure 5.5: This graph shows the results of the material test. The solid lines represent IEEE802.15.4 values and the dashed lines represent LoRa values.
The color of the lines represent the material: blue = brick, red = wood, green = cardboard, yellow = plastic.

5.5 Accuracy and Precision Tests

Figure 5.6 shows all the test points that were used to evaluate the LoRa and GPS receivers outdoors while Figure 5.7 shows the indoor locations. From these points, the accuracy and precision was determined by inspection and use of computer software(Inkscape[44]) to obtain τ and Δ.

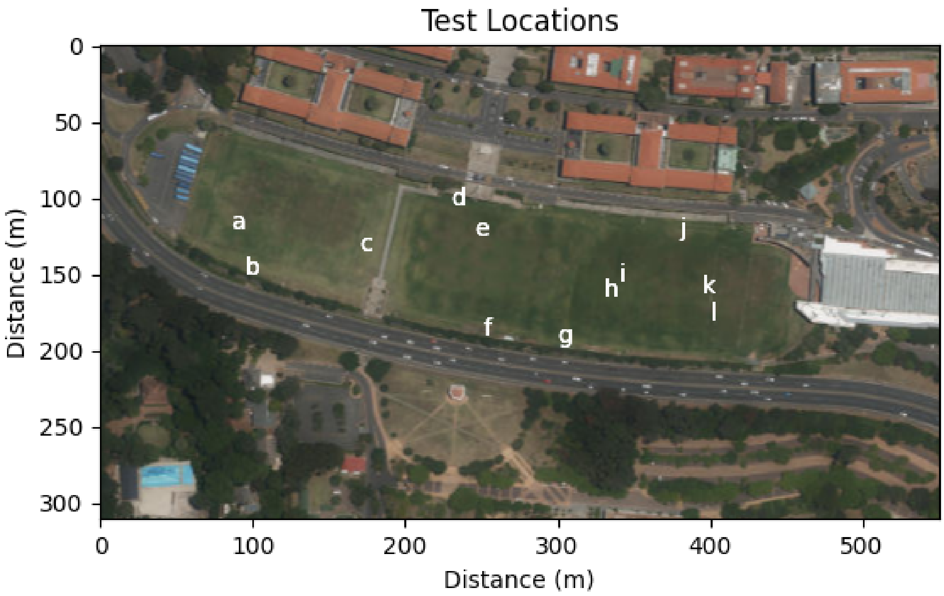

Figure 5.6: A map of the points that were used to evaluate the different receivers outdoors. a = 1, b = 2,...,l = 12.

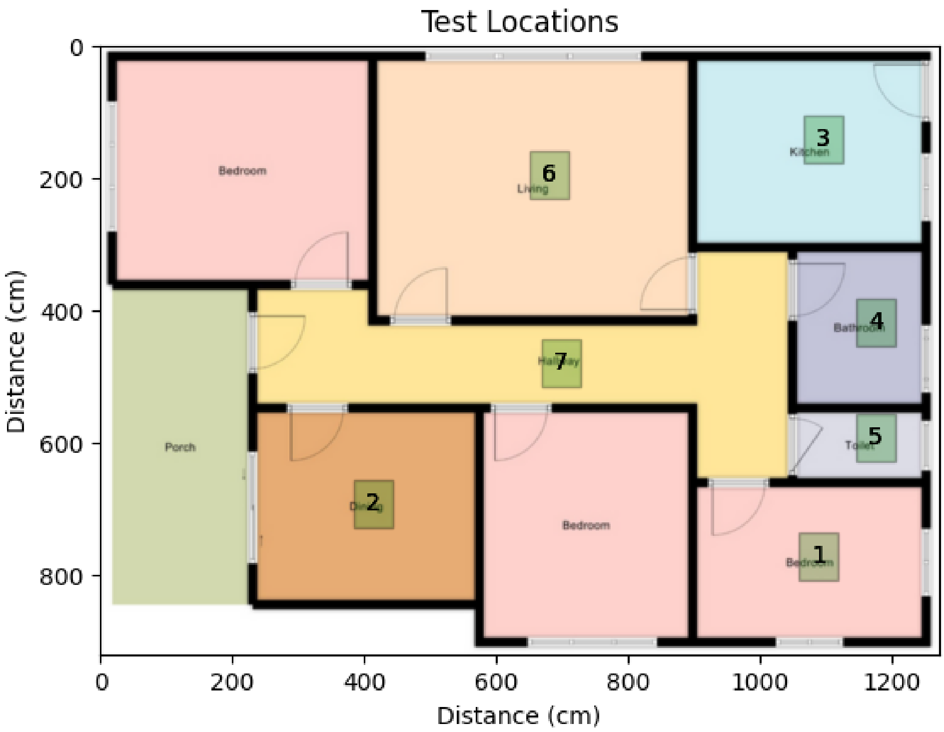

Figure 5.7: A map of the points that were used to evaluate the different receivers indoors.

Figure 5.8 shows the 12 locations that were obtained by the GPS receiver. These were captured after the mobile application indicated the lowest possible accuracy.

Figure 5.8: A map of the points as estimated by the GPS receiver.Map obtained from Google Earth.

Figure 5.9 and Figure 5.10 are compiled from the accuracy information from Table A.5 and Table A.7. This is obtained to give an indication of how accurate LoRa could be when compared to GPS outdoors and indoors respectively.

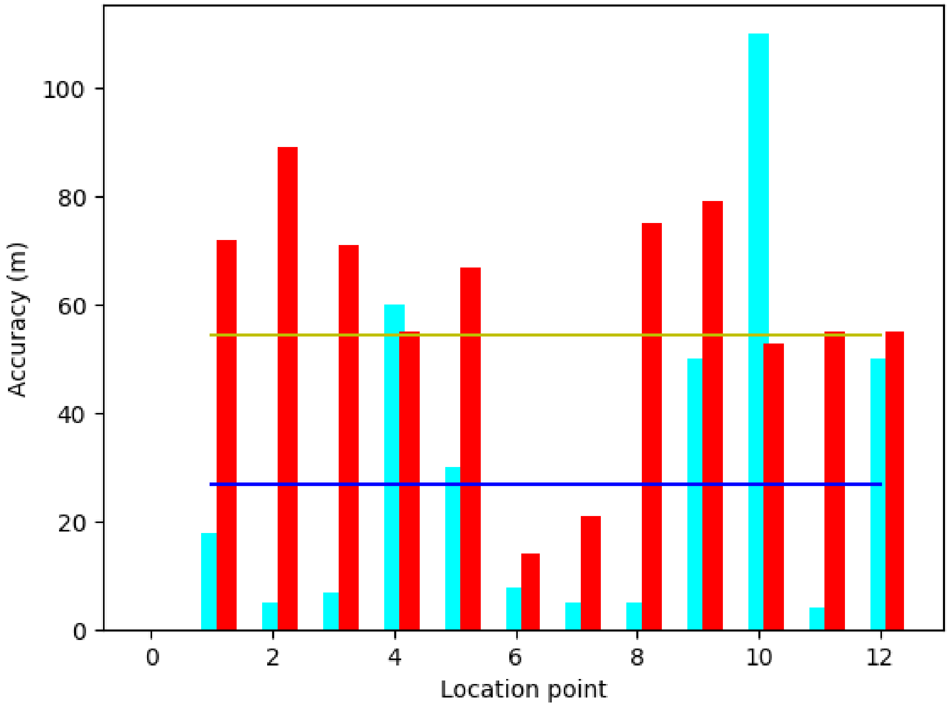

Figure 5.9: Accuracy of GPS(aqua) and LoRa(red) with the average accuracy being indicated by the blue and yellow for GPS and LoRa respectively for outdoor tests.

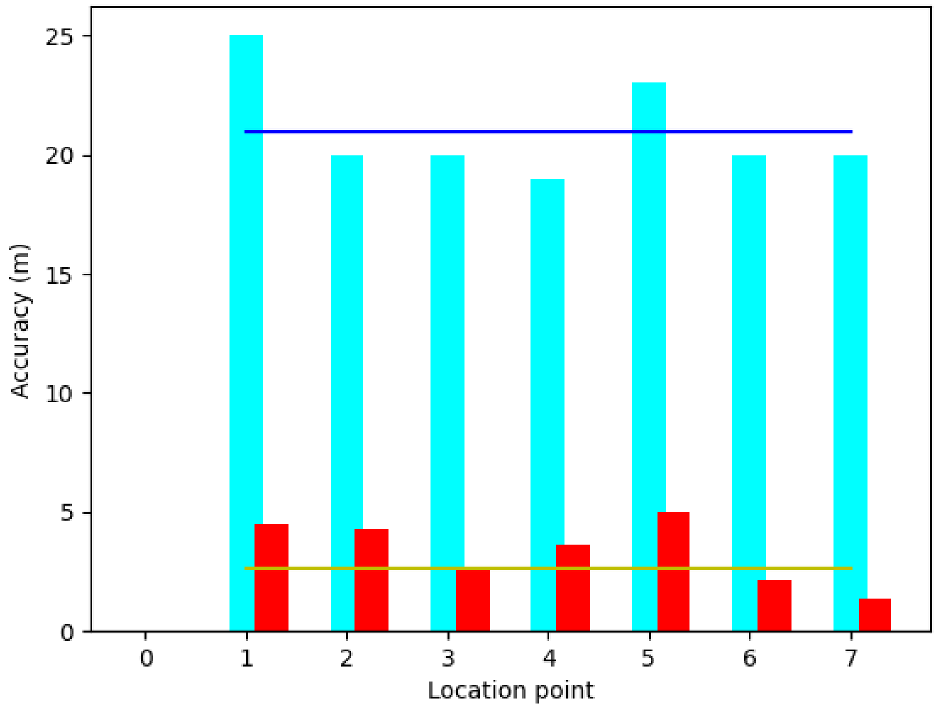

Figure 5.10: Accuracy of GPS(aqua) and LoRa(red) with the average accuracy being indicated by the blue and yellow for GPS and LoRa respectively for the indoor tests.

With regard to the LoRa network's precision, Figure 5.11 and Figure 5.12 show the variations in precision with each of the test locations for outdoor and indoor tests respectively.

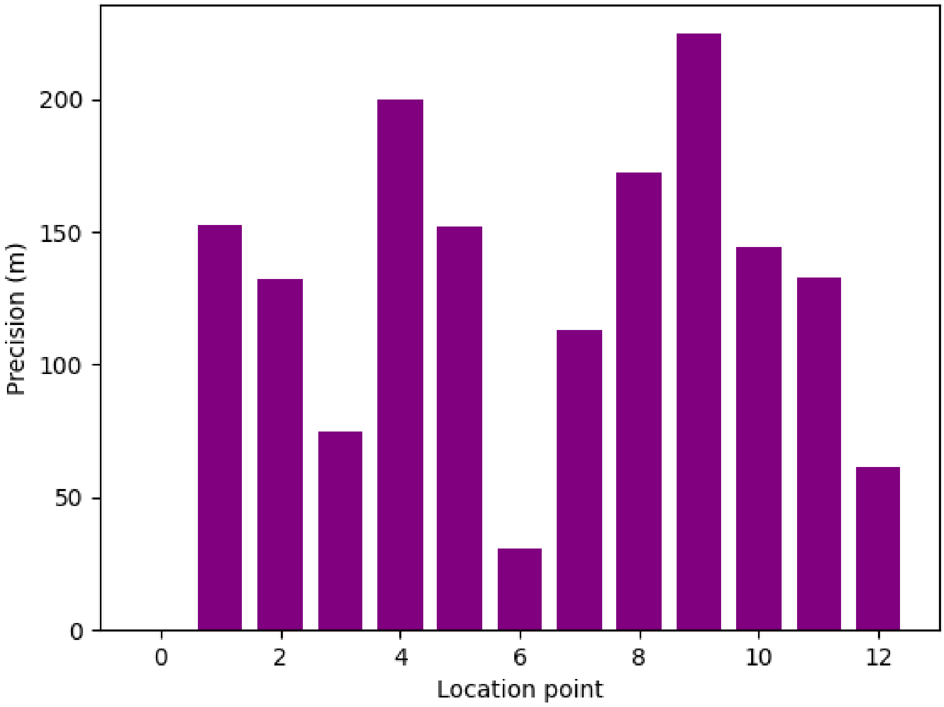

Figure 5.11: Precision of LoRa at the 12 outdoor test points that were used.

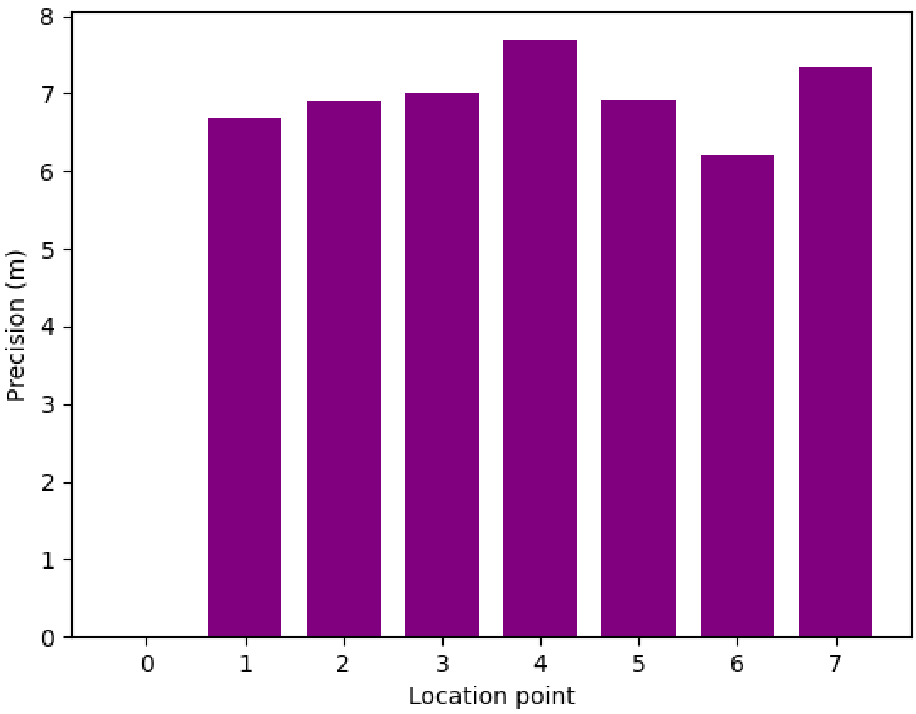

Figure 5.12: Precision of LoRa at the 7 indoor test points that were used.

5.6 Final Comparison

Table 5.9: Final comparative details for all networks that were analyzed outdoors in this investigation.
* This lifetime is an approximation as a result of multiple other factors draining the phone's battery
** Data for precision is not available as this device was not evaluated physically.

Network	Precision (m)	Accuracy (m)	$\text{Cost}_{transmitter}$ (ZAR)	$\text{Cost}_{receiver}$ (ZAR)	Expected Lifetime (days)
IEEE802.15.4	-	-	612.23	612.23	25.5
LoRa	124.1	58.7	742.23	742.23	20.12
A-GPS*	29.3	29.3	0	5500	<1
GPS**	-	-	0	524.23	2

Table 5.10: Final comparative details for all networks that were analyzed indoors in this investigation.
* This lifetime is an approximation as a result of multiple other factors draining the phone's battery
** Data for precision is not available as this device was not evaluated physically.

Network	Precision (m)	Accuracy (m)	$\text{Cost}_{transmitter}$ (ZAR)	$\text{Cost}_{receiver}$ (ZAR)	Expected Lifetime (days)
IEEE802.15.4	4.14*	8.30*	612.23	612.23	25.5
LoRa	3.37	6.96	742.23	742.23	20.12
A-GPS**	29.3	29.3	0	5500	<1

Chapter 6

Discussion

This chapter will look at the results obtained in Chapter 5 and carefully analyze them to see if they conform to previous patterns exhibited in some of the past work that was brought up in the Chapter 2. It will also present some explanations for some of the results that were obtained.

6.1 General notes

Some of the intended tests did not end up being completed or had inadmissible results due to some of the issues encountered. These tests and reasons are detailed below.

- Test L3 was not done as the range of the field used was not large enough. The maximum possible distance was 400m.
- Rest X4 could not be done as there was a lack of receivers capable of use. A power supply issue was found on the transceiver module that did not allow the transmitter of the MRF24J40MA to send packets. This was later rectified but only to conduct tests X1 - X3 and X5. The new repaired board for this can be found in Figure A.3.

6.2 Range Tests

One key observation was with regard to the range of the devices when in localisation mode. For the LoRa network, once all beacons were on, the received signal decreased from the previously expected values. This may have been because of the now busy RF environment filled with unnecessary packets being sent around.

With regard to the material tests shown in Figure 5.5, a key change variation change can be seen for the IEEE802.15.4 radio where between 2 and 3 metres, the variation is not as expected. This may be a pitfall of the PCB antenna having dead zones or weak zones.

6.3 Power Tests

It was keenly noted that the LoRa network used much more power than the IEEE802.15.4 network. The expected lifetimes of the different networks were also shown in Table 5.9. The results also indicate that a LoRa network would live 10 times longer than a standard GPS network while the IEEE802.15.4 network would live at least 12 times longer.

Looking back at the work of Dinh[1], the results using a bigger capacity battery yielded a much longer battery life of six days. The longest possible battery life for the optimized GPS receiver was caught at 27 days. Compared to the current results, the LoRa network may match the optimized GPS receiver but the IEEE802.15.4 network is likely to yield a longer life.

6.4 Cost Analysis

With regard to costs, the clear winner would be the GPS network as it is the cheapest to implement as shown in Table 5.9. The reason the cost of the transmitter is R0 is because the onus to launch a GPS satellite is not on the user and obtaining data from these satellites is also free. The same is true for the A-GPS receiver where a user would only need a cellphone plan with their carrier to access the service.

The A-GPS system would be the most expensive because the receiver being used is a mobile phone which comes with more functionality that is needed for such an installation however its results for accuracy and precision were needed. What is important to note however is that for the IoT devices, the cost realistically varies with the use case. If localisation was added to the network as an added feature, the cost of the transmitters would only be that of the radios found in Table 5.3 or even R0 if the radios were already in use as the change would only be in software. This would be done where there is a preexisting deployment of IoT devices. For the case where there are no devices installed and a new deployment is needed, the prices in Table 5.9 would suffice.

6.5 Accuracy and Precision

Table 6.1: A statistical analysis of the accuracy and precision of GPS and LoRa for the outdoor tests.

	τ_{GPS} & Δ_{GPS} (m)	τ_{LoRa} (m)	Δ_{LoRa} (m)
Mean	29.33	58.70	124.10
Standard Deviation	32.76	22.34	58.97
Variance	1072.97	499.16	3477.38

With regard to accuracy, average values from the LoRa data set were obtained for outdoor tracking and compiled to come up with an mean accuracy of 58.7m as shown in Table 6.1. The precision of GPS is considered to be the same as its accuracy because the assumption is that the location estimated by the receiver is at the center of it's accuracy circle.

When compared to the results from Choi et al's[28] investigation, this study produced a worse accuracy for LoRa while using an inferior processing step which is expected. When compared to Henriksson's report[27], the simulations results are close to those obtained in this investigation with a similar technique being used and the number of nodes being taken as three. This confirmation show the consistency of the devices in simulation and in deployment.

With regard to precision, more work would need to be done on this front so as to allow better localisation. This would be the key feature in rating the effectiveness of a network's usability with regard to localisation. Effectively, when compared to the accuracy, this value should be as close as possible to that and for the case of LoRa outdoors, the mean precision is slightly over double the mean accuracy.

Table 6.2: Summary of all the indoor tests.
* Results not admitted due to insufficient equipment to achieve successful localisation.

Position	τ_{GPS} & Δ_{GPS}	τ_{LoRa}	Δ_{LoRa}	$\tau_{IEEE802.15.4}$*	$\Delta_{IEEE802.15.4}$*
1	25	4.49	6.68	9.08	1.02
2	20	4.31	6.90	0.82	9.13
3	20	2.63	7.01	0.36	7.86
4	19	3.65	7.68	2.47	14.24
5	23	5.00	6.93	15.00	18.35
6	20	2.13	6.20	0.00	0.00
7	20	1.39	7.34	1.27	7.54
Mean	21.00	3.37	6.96	4.14	8.30
Standard Deviation	2.16	1.35	0.47	5.71	6.58
Variance	4.67	1.82	0.22	32.63	43.26

With regard to the preliminary results shown in Table 6.2, there can be high hopes for IEEE802.15.4 being a very strong option for indoor localisation. It would not be as good as the LoRa devices however which have a mean accuracy of 3.37m. What is however clear is that the GPS results are very far off from those obtained for the IoT networks.

Comparing the differences however between indoor and outdoor localisation, GPS, as expected, performs worse than indoors that outdoors, however it is more consistently worse indoors as opposed to outdoors where it sporadically has bad readings. Thought the mean was higher outdoors for GPS, it's lowest accuracy value was much smaller than that of of the indoor tests. As for LoRa, It performed much better indoors. This may be due to the greater losses withing the environment leading to finer resolution for RSSI readings. This means that while the overall range may decrease, the accuracy and precision increase, which may be an advantage depending on the use case.

Chapter 7

Conclusions

Having assessed LoRa, GPS and IEEE802.15.4 receivers, it has become clear that there is still work to be done in this field of study. The biggest gap which this study did not look at with empirical data would be the power consumption of the IoT networks during localisation with a sufficient algorithm. With the simulation data that was obtained, however, it was possible to conclude that the IoT networks would last longer with a single battery charge than GPS. The only drawback would be the cost where the price of getting the radio would be more than that of a GPS receiver if building a specialised localisation network. If used as an add-on service to existing deployments, however, the cost of doing so would be very small and in this case be better off than adding GPS receivers.

The next key metrics to examine would be the IoT vs GPS precision and accuracy. Although they are greatly influenced by the localisation technique used, it was noted that the LoRa outdoor tests greatly matched the results from past investigations with an accuracy of 58.7m and a precision of 124.1m. The indoor tests were however much better, yielding an accuracy of 3.37m and a precision of 6.96m. This indicates the benefits to urban localisation path loss as the RSSI resolution becomes more fine. The GPS results for precision and accuracy indoors was 21m and for the outdoor tests was 30m. This means that the indoor IoT localisation case performed better than GPS as opposed to the outdoors where GPS was better.

Overall, the investigation may be considered as incomplete with results pending confirmation. This is because of the IEEE802.15.4 localisation technique not being coherent with that used by LoRa and GPS. If the preliminary results were to be accepted, the investigation would be considered complete. Taking theoretical data, however, shows that the range of LoRa is greater than 10km, it is fair to conclude that it is the better solution for asset tracking across large multisite factories as opposed to IEEE802.15.4 who's outdoor range is not expected to be greater than a kilometer. Regarding the cost, it was noted that the LoRa radio may have been cheaper. Finally, the power metrics when compared to GPS were favorable for storage time under a month as opposed to GPS which would last for 2 days.

Chapter 8

Recommendations

Having completed the investigation, some key areas were found that needed much attention and future researchers may look into them to further improve the body of work related to localisation.

Power Consumption

This is the major area where more accurate work needs to be done as the presented investigation only used simulation results and not real world results. The use of an ammeter with a resolution 10nA would be sufficient to appropriately conclude the power consumption of the device.

GPS and A-GPS

The use of a dedicated GPS receiver would also have allowed a more even playing ground for the devices in this investigation. By using a mobile phone, the power consumption and cost results would not be fairly matched to those shown by the IoT networks.

Transceiver Design

Most of the issues and hindrances in this investigations were results of poor design on this front. Firstly, using a custom made PCB would be advised with sufficient allowances for the radio transmission devices. Furthermore using a better voltage regulator to not encounter issues that may arise when it came to transmission. Finally, there exists a lower power version of the microcontroller used in this investigation. If this or any other cheap and low power microcontroller were used for this investigation with sleep cycles activated, much useful data may be obtained and used to validate the conclusions of this report.

Further investigations

If more time and equipment was available, the following investigations may have been conducted so as to find how IoT localisation may be affected.

Interchanging dynamic maps in similar confined spaces

Given that multiple dynamic maps will be created, it would be nice to find out if the maps could be interchangeable e.g. do urban building respond the same? or does and open field test yield the same results indoors or in a mall?

Beacon Formation

This looks into the shape that the beacons are placed in. Questions that may be asked include figuring out if an equilateral triangle yields better results than an isosceles?

Minimum point indoor dynamic mapping

By doing the initial range measurements in each room or at all corners of an open space and populating the range arrays for each radio. For indoor mapping, this can be done by obtaining one measurement from the center of each room and using that as the reference from each beacon.

Changing the transmitter power

Does this affect the RSSI sensitivity range? Would this help make long distance WANs such as LoRa more accurate?

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[44] Inkscape, "About — Inkscape."

Appendix A

Additional Files and Schematics

A.1 Code

All of the code used in the project is contained in the Github repository found at https://github.com/chirambaht/Assessment-of-LoRa-and-IEEE802.15.4-suitability-for-asset-tracking-across-an-urban-environment.git The available software is documented in the various sub-modules that this repository contains.

A.2 Proposed deployment architecture

A.2.1 Firmware

The proposed firmware design should follow the following flowchart to allow mass localisation.

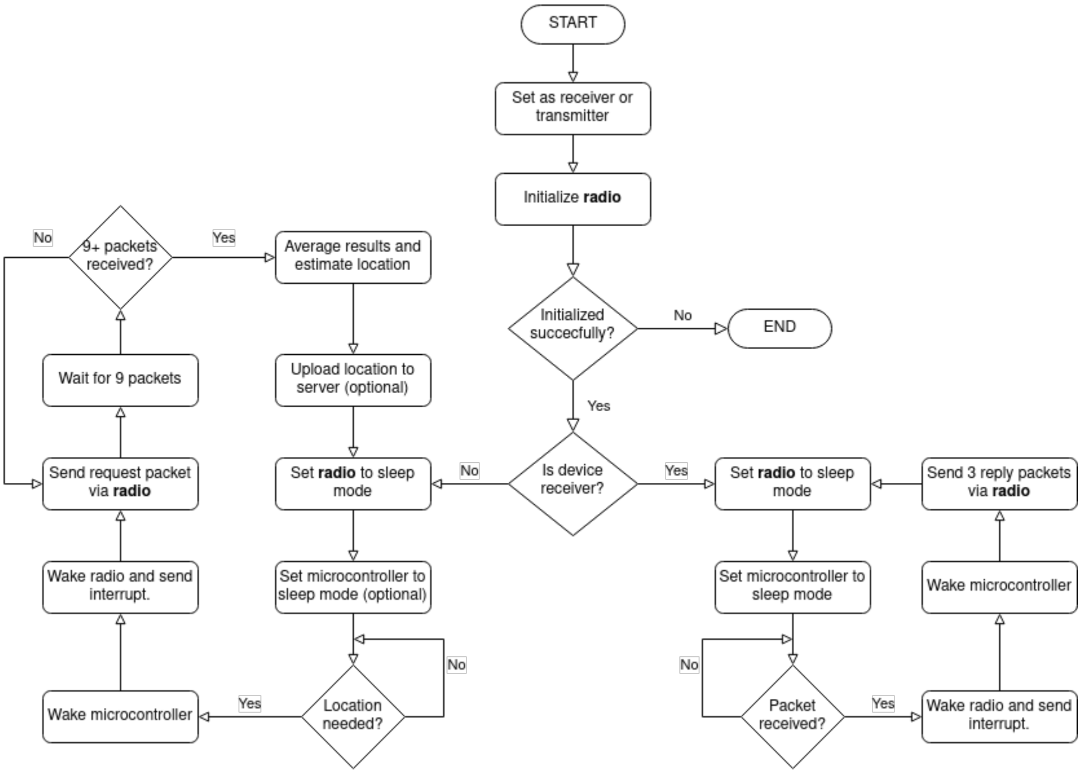


Figure A.1: Proposed software design for a deployed solution. This is a generic flowchart and 'radio' must be replaced with the intended deployment LPWAN transceiver.

A.3 Extension Board

Below are images of the receiver extension board that was used in the investigation.

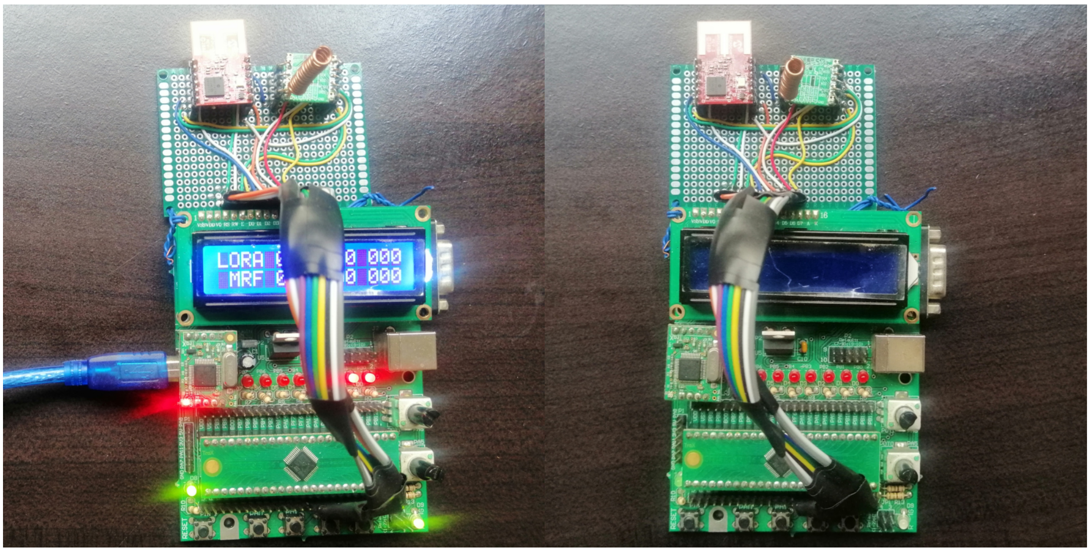
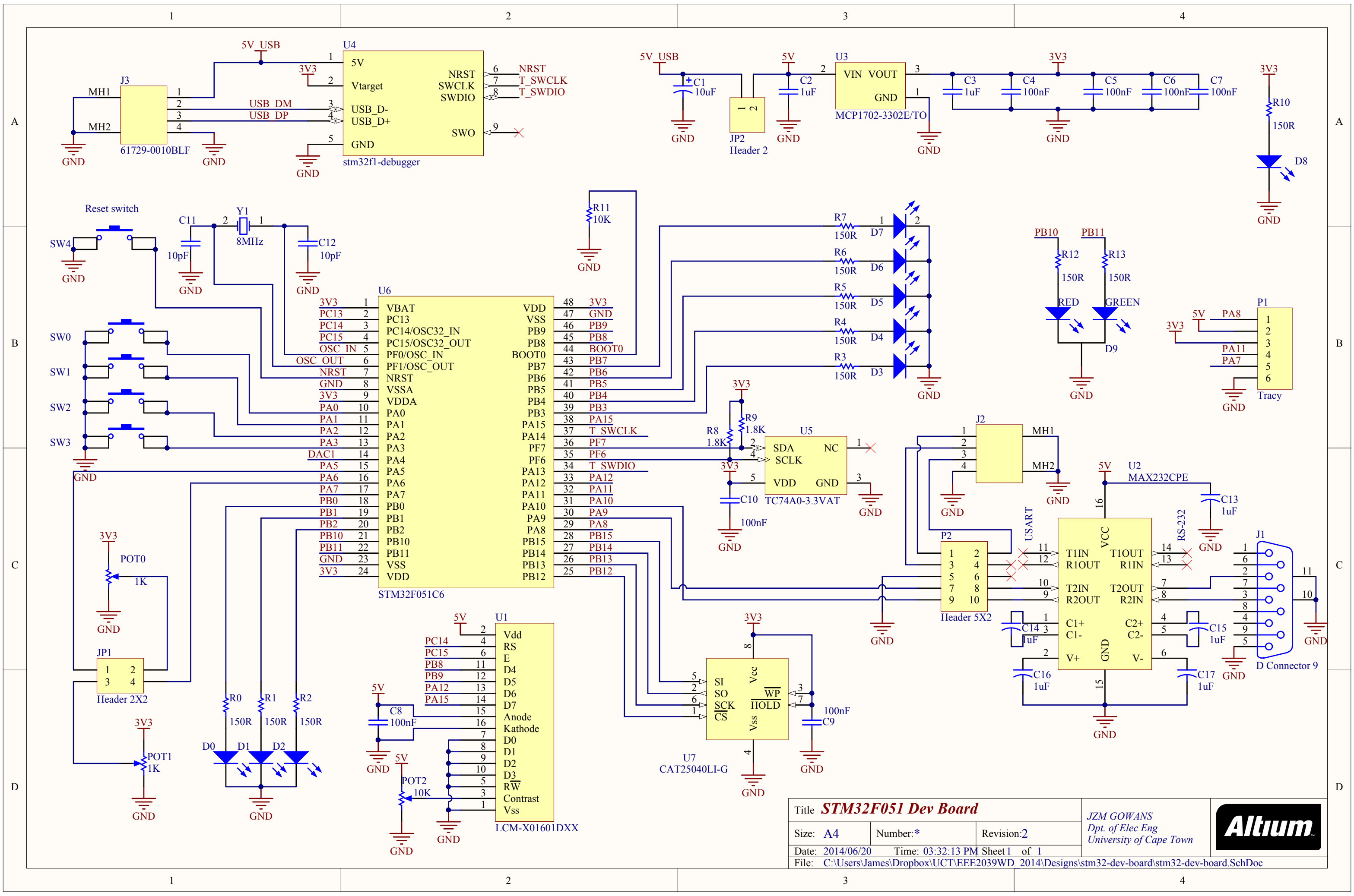


Figure A.2: The receiver development board that was used as the location device. On the left is an image of the board in use.

The schematic for the extension board and how it interacts with the LoRa and IEEE802.15.4 radio is shown in Figure A.2.

The schematic for the development board is shown below. It was designed by James Gowans.


Title STM32F051 Dev Board
Size: A4
Number: *
Revision: 2
Date: 2014/06/20
Time: 03:32:13 PM
Sheet 1 of 1
File: C:\Users\James\Dropbox\UCT\EEE2039WD 2014\Designs\stm32-dev-board\stm32-dev-board.SchDoc
JZM GOWANS
Dpt. of Elec Eng
University of Cape Town
Altium
U4 stm32f1-debugger
J3 61729-0010BLF
U3 MCP1702-3302E/TO
JP2 Header 2
Reset switch
Y1 8MHz
U6 STM32F051C6
U5 TC74A0-3.3VAT
J2
P1 Tracy
P2 Header 5X2
U2 MAX232CPE
USART
RS-232
J1 D Connector 9
JP1 Header 2X2
POT0 1K
POT1 1K
POT2 10K
U1 LCM-X01601DXX
U7 CAT25040LI-G

A.4 MRF24J40 Transmission Fix

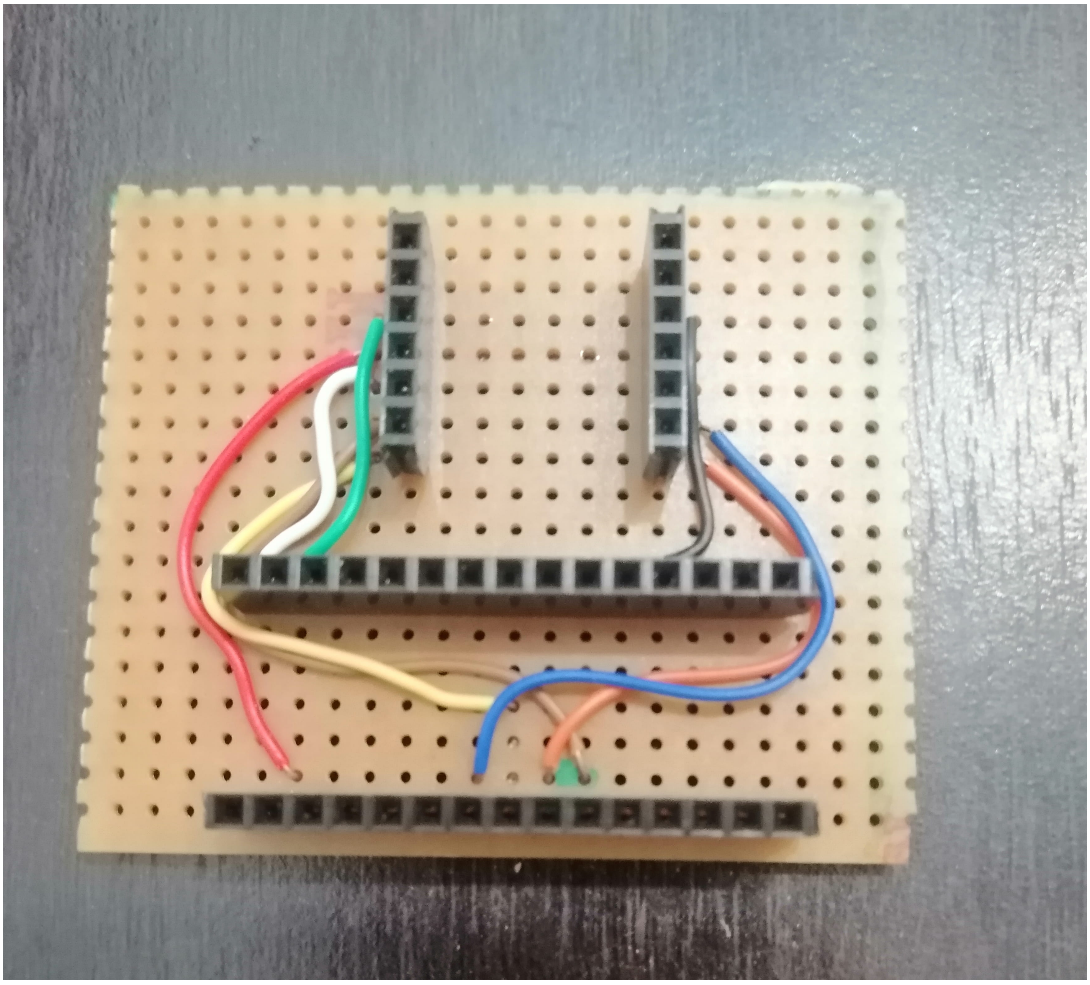


Figure A.3: The fixed MRF transmitter board that can transmit messages.

A.5 Power Consumption Results

Table A.1: Results based on datasheet values on the power consumption of the individual modules. This list includes the UBlox Neo-6M power results.

Radio	**Mode**	$\mathbf{I}_{radio}$ **(mA)**	$\mathbf{I}_{\mu C}$ **(mA)**	**Time (ms)**	**Power (mW)**
LoRa	Reception	12.1	10.5	10	246.1
	Transmission	120	10.5	10	1421.1
	Sleep	0.0015	5.9	1000	64.3
IEEE802.15.4	Reception	19	10.5	10	321.3
	Transmission	23	10.5	10	364.8
	Sleep	0.002	5.9	1000	64.3
Neo-6M	Reception	47	10.5	3000	626.2

	Sleep	11	5.9	1000	184.0

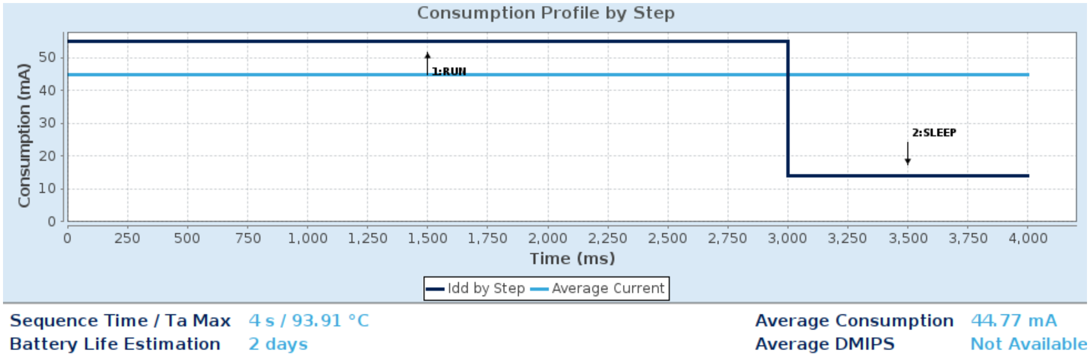


Figure A.4: Obtained power consumption results of the GPS radio in Assisted receive mode for 3 seconds(maximum TTFF) and 1s sleep cycle running on a 2200mAh battery. Calculated by STMCubeIDE's Power Consumption Calculator.

A.6 Cost Analysis

Table A.2: Results of the cost based on the listed prices in the bill of materials. This table includes the Ublox Neo-6M GPS module costs.

Radio	Cost$_{\mu C}$ (ZAR)	Cost$_{radio}$ (ZAR)	Cost$_{extra}$ (ZAR)	Total (ZAR)
LoRa	210.00	390.00	142.23	742.23
IEEE802.15.4	210.00	260.00	142.23	612.23
Neo-6M	210.00	172.00	142.23	524.23

A.7 Range Testing

Table A.3: Full table of results, based on Table 4.1, of the range tests conducted for the LoRa radio.

Distance (m)	RSSI$_1$	RSSI$_2$	RSSI$_3$	RSSI$_{average}$
0	255	252	253	253
1	242	245	244	244
2	242	239	241	241
3	193	196	193	194
4	190	189	191	190
5	188	188	189	188

20	183	182	183	183
40	178	181	179	179
60	175	174	176	175
80	170	172	173	172
100	169	169	168	169
120	167	168	167	167
140	166	165	169	167
160	164	163	164	164
180	159	162	158	160
200	162	163	161	162
250	159	157	158	158
300	162	168	161	164
350	158	156	157	157
400	146	148	149	148

A.8 Precision and Accuracy

Table A.4: Table showing all the data collected for LoRa for the outdoor tests.

Location	**Tower**$_A$	**Tower**$_B$	**Tower**$_C$	**A**$_{average}$	**B**$_{average}$	**C**$_{average}$
1	163 165 165	149 146 148	153 152 153	164	148	153
2	166 165 171	156 156 162	166 149 147	167	158	154
3	171 177 170	162 158 153	150 140 141	173	158	144
4	162 158 156	153 164 160	147 158 150	159	159	152
5	158 159 157	157 168 170	157 157 153	158	165	156
6	149 147	179 176	160 166	148	180	162

	149	184	161			
7	154 152 151	157 165 162	162 152 162	152	161	159
8	146 147 147	160 159 154	161 162 163	147	158	162
9	146 150 146	163 162 153	160 150 162	147	159	157
10	149 143 143	162 162 161	165 162 162	145	162	163
11	144 144 147	162 159 168	166 167 168	145	163	167
12	142 143 145	161 161 162	178 174 173	143	161	175

Table A.5: The true, estimated and farthest from center points for the results obtained from the outdoor LoRa radio test.

	True Point (cm)		**Estimate (cm)**		**Furthest (cm)**			
	x	**y**	**x**	**y**	**x**	**y**	τ **(m)**	Δ **(m)**
1	85	120	145	81	121	232	71.56	152.90
2	95	150	156	85	115	211	89.14	132.50
3	170	135	140	71	215	70	70.68	75.01
4	230	105	194	146	64	298	54.56	200.01
5	245	125	255	191	104	173	66.75	152.07
6	251	190	265	190	258	160	14.00	30.81
7	300	195	294	175	188	135	20.88	113.30
8	330	165	389	118	404	290	75.43	172.65
9	340	155	271	193	491	148	78.77	224.56
10	380	125	336	155	399	285	53.25	144.46
11	395	162	341	153	286	32	54.74	132.91
12	400	180	378	130	364	70	54.63	61.61

Table A.6: Table showing all the data collected for LoRa for the indoor tests.

Location	**Tower**$_A$	**Tower**$_B$	**Tower**$_C$	**A**$_{average}$	**B**$_{average}$	**C**$_{average}$
1	194 192 193	184 189 189	179 183 187	193	187	183
2	187 182 182	182 179 179	183 182 181	184	180	182
3	181 170 184	182 183 183	239 242 241	178	183	241
4	185 186 190	242 241 243	180 182 192	187	242	185
5	177 187 187	183 182 182	182 187 182	184	182	184
6	176 173 175	178 174 178	178 183 183	175	177	181
7	190 191 185	191 190 186	191 174 179	189	189	181

Table A.7: The true, estimated and farthest from center points for the results obtained from the indoor LoRa radio test.

	True Point (cm)		**Estimate (cm)**		**Furthest (cm)**			
	x	**y**	**x**	**y**	**x**	**y**	τ **(m)**	Δ **(m)**
1	1076	781	740	483	117	725	4.49	6.68
2	402	702	702	392	84	700	4.31	6.90
3	1083	151	832	228	230	587	2.63	7.01
4	1163	428	820	553	53	581	3.65	7.68
5	1163	602	712	387	61	625	5.00	6.93
6	668	205	653	417	148	776	2.13	6.20
7	686	490	738	361	117	753	1.39	7.34

NB: A single tower was used for the indoor MRF tests.

Table A.8: Table showing all the data collected for IEEE802.15.4 for the indoor tests.

Location	**RSSI**$_1$	**RSSI**$_2$	**RSSI**$_3$	**RSSI**$_{average}$
1	55	51	52	53
2	96	97	98	97
3	120	115	115	117
4	73	77	84	78
5	24	33	27	28
6	249	251	252	251
7	117	116	120	118

Table A.9: The true, estimated and farthest from center points for the results obtained from the indoor IEEE802.15.4 radio test.

	True Point (cm)		**Estimate (cm)**		**Furthest (cm)**			
	x	**y**	**x**	**y**	**x**	**y**	τ **(m)**	Δ **(m)**
1	1076	781	0	1000	-20	900	9.08	1.02
2	402	702	410	620	1080	0	0.82	9.13
3	1083	151	1050	166	310	430	0.36	7.86
4	1163	428	1209	671	-30	-30	2.47	14.24
5	1163	602	-337	602	1498	602	15.00	18.35
6	668	205	668	205	668	205	0.00	0.00
7	686	490	650	612	0	994	1.27	7.54

Appendix B

Addenda

B.1 Ethics Form

ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Humphrey Tinashe Chiramba
Department		Electrical Engineering
Preferred email address of applicant:		chirambaht@gmail.com
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc Electrical and Computer Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	40
	Name of Supervisor (if supervised):	Jane Wyngaard
If this is a researchcontract, indicate the source of funding/sponsorship		N/A
Project Title		Low cost, low power location tracker

I hereby undertake to carry out my research in such a way that:
- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Humphrey T Chiramba		16/08/2020
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	Jane Wyngaard		17/08/2020

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).			
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			