An Active Low Cost Mesh Networking Indoor Tracking System

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***Abstract* - Indoor radio frequency tracking systems are generally quite expensive and can vary in accuracy due to interference, equipment quality or other environmental factors. Due to these limiting factors of the technology, many businesses today find it hard to justify investing in RFID tracking technologies to improve the safety, efficiency and security of their working environments. The aim of this project was to provide a budget RFID tracking system that was capable of tracking a person or object through an indoor environment. To minimize the cost of the RFID tracking system, the components of the system were built from existing electronic equipment and hardware. The software was also written to minimize licensing and support fees allowing a cost effective budget RFID tracking system to be developed. The tracking system consists of a tag, reader nodes and a PC reader which utilize synapse RF 100 engines with python scripts embedded on to the chips.**

I. INTRODUCTION

Real Time Location Systems (RTLS) are becoming increasingly integrated within everyday society and large corporations. Although RFID has many potential benefits and is consider quite accurate in tracking people and assets within an indoor environment, the technology itself is considered to be expensive requiring many tags, readers and software to be purchased. Hence the technology has not been widely adopted by smaller end businesses and public sector service providers managed by the government. Many of these businesses are constrained by a budget, which is affecting their need to improve processes via investing in wireless tracking technology. There has been many wireless indoor tracking systems developed to date, often deployed in prisons, super markets, supply chains and within the farming industry. These existing approaches all have common features and have all encountered a similar drawback that is an inherent problem with the use of wireless for tracking. There is a neglect to cater for the lower end and smaller business to improve their efficiencies and processes through the utilization of wireless tracking technologies. For wireless tracking technology to be truly widely adopted this issue must be addressed and a lower budgeted solution must be investigated and made available. The drawback is the price of the hardware. This research hopes to address and demonstrate that inexpensive and effective solution is viable.

This research aims to present a mesh based indoor wireless tracking system that will be capable of tracking a person or asset within an indoor environment. We can demonstrate here that not only the tracking software can be designed and developed but also the actual wireless hardware such as the tags and readers needed to track a person or object can be built from existing hardware components. The software can be written to integrate with each of these homemade tracking components to produce an accurate and reliable wireless tracking system. A Mesh network is a LAN (usually wireless) where each node is connected to many others, configured to allow connections to be rerouted around broken or blocked paths, with the signal hopping from node to node until it reaches its destination [1]. A wireless mesh network has advantages over other network topologies. Once set up, a wireless mesh network can manage its load to avoid clogging a certain network node. If one node becomes busy, the network traffic is redirected through other nodes, maintaining a good balance of the network load. They rely on the same WiFi standards (802.11a, b and g) already in place for most wireless networks allowing them to be easily fitted into already existing systems using the same protocols. Wireless mesh networks are easily expanded due their node structure once a new node is added the whole network can immediately use it within its data routes. The system outlined here is mesh based with a web-based portal that will allow the user to monitor the tags location, status and information. The purpose of building the location determination equipment is to demonstrate that an indoor tracking system does not have to be expensive and developers do not have to purchase costly premade readers or tags but that an effective wireless tracking system can be developed with a budgeted approach. This budget approach would essentially offer small to medium sized businesses an effective tracking system with an attractive price tag.

II. LOCATION DETERMINATION TECHNOLOGIES

Location determination technologies are the technologies used and are capable of producing real time location systems. Real time location systems capture, process and store location specific data [2]. This section outlines many technologies that can and are being used to today to produce people and asset

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tracking systems. Mobile cellular systems can locate mobile systems (MS) by using the various methods of measuring the radio signals traveling between the mobile system and a set of fixed base stations (BS) or cellular towers. The signal measurements are first used to determine the length or direction of the radio path, and then the MS position is derived from known geometric relationships [3]. A location can be determined through mobile cellular systems by two key methods known as signal attenuation and time of arrival (TOA). Signal attenuation can locate a mobile system by measuring the signal strength of the system against three or more base stations also known as multilateration and determining the location by calculating the distance the mobile device is from the base stations/cellular towers by the strengths recorded. [4] identified that "the main problem of this approach is the accurate estimation of the signal strength in a multipath fading environment and particularly how this relates to distance, given that the fading characteristics may be different in the directions of the three BSs". Although the accuracy of using mobile cellular systems can be deemed at times inaccurate due to signal interference caused by adverse weather conditions and the fact that it is an estimation of location and not exact location the technology can still be used to benefit some industries such as the transport industries. Knowing the position of vehicles in a transport system, e.g., allows for an efficient planning and use of resources [5]. ZigBee is the set of specs built around the IEEE 802.15.4 wireless protocol. The technology can be described as smart, low cost, low maintenance, low powered and efficient. ZigBee is compatible with most topologies including peer-to-peer, star network and mesh networks, and can handle up to 255 devices in a single WPAN. ZigBee allows the seamless communication of devices running the protocol, which is perfect for developing small-scale monitor and control systems. Many products already support the wireless protocol 802.11 a/b/g/n and many support connecting to each other through Wi-Fi networks. Recently, a growing interest of the scientific community in techniques that rely on IEEE 802.11 local area networks has been appreciated, since this type of communications infrastructure is being deployed in most of buildings and hence allows the design of flexible and low-cost positioning systems [6]. Wireless networks are fully capable of tracking the movements of an object through its network and access points (AP's). Bluetooth is a short-range wireless technology, which was developed for low-cost, low-bandwidth communication scenarios [7]. Bluetooth like many other location tracking technologies was primarily developed for communication but it is slowly being adapted in a number of ways to be utilized for location-based tracking. Bluetooth has had a number of experimental tracking systems developed many of which use nodes which are much like wireless access points (AP's).

Radio Frequency Identification (RFID) is any system of identification wherein an electronic device that uses radio frequency or magnetic field variations to communicate and is attached to an item [8]. RFID is a widespread technology and is currently being used worldwide to solve a variety of problems and issues. The RFID tag also known as a transponder is the piece of integrated circuit that is placed onto an individual object, the transponder has a digital memory and has a unique product identification code which allows the tag to be uniquely identified. The transponder is responsible for storing data/information on the object, power management, broadcasting and intercepting radio frequency signals. RFID tags can be labelled into two distinct groups know as Active and Passive tags. Passive tags have no onboard power supply. [9] states that passive tags consume power provided by the reader through inductive coupling and they only operate in the presence of a nearby reader. [10] enforces this stating passive tags are most often used for short read-range applications (<1.5 m) and require a high-powered reader with antenna capable of reading the information. This is the main drawback for passive tags as they need to be close or pass a reader to function, which limits their range of use. The fact that passive tags do not have their own power supply is in ways beneficial as the tags are cheaper to produce and they have a very generous life expectancy as they can last for decades which means this will lower maintenance costs [11].

A LOW COST TRACKING SYSTEM - DESIGN

This section provides a detailed outline of the design of a low cost Zigbee wireless tracking system. There are many technologies capable of tracking people and assets. The problem that we are addressing is the costs of most of these systems. We aim to outline a tracking system capable of tracking people and assets in an indoor and potentially cramped environment which is accurate, relatively low cost to build and develop and ultimately reliable. Wireless tracking systems can be expensive, to limit the expense of the developing the system for this project each component of the tracking system will be built, which includes the RFID tags, RFID readers and PC reader. This will allow a low cost solution to be developed and will also allow the systems hardware components to be easily upgraded to enhance the system in the future. The tracking system is built from scratch. This required the sourcing and acquiring of the individual hardware components necessary to build a wireless tag, pc-reader and multiple reader nodes. These components can be bought from many electronic stores and wholesale suppliers such as synapse radio frequency engines, which will be used to transmit and receive the radio frequencies between the devices. Buying the components separately and building the tracking devices can keep costs to an absolute minimum.

Software required in order to develop the RFID tracking system included Synapse Portal (version 2.4.17) for creating and transferring python scripts onto each of the RF100PC6 Synapse RF Engine's. These python scripts run on the RF engines and allow the position of the tag to be transmitted. Microsoft Visual Studio 2010/Visual C# Express edition as a C# script required to forward the location data received from the PC reader to the web portal. Notepad ++ - or similar for writing the web portal using HTML, PHP and JavaScript and PhpMyAdmin to create and manage the MySQL database to hold the RFID tags tracking information recorded by the reader nodes and will also record Meta information associated with the tag.

The transponder will awaken on a set regular interval and broadcast its location to the reader nodes. The RFID will be asleep and will only awaken to broadcast its signal as the RFID tag will be battery powered and this will conserve energy. The reader nodes unlike the RFID tags will be powered by the mains power supply and will have a steady income of electricity. The reader nodes will be constantly listening in the mesh network for the RFID tag to broadcast a signal so the reader nodes can capture the signal strength and pass this information through the mesh network and to the PC reader node. The PC Reader Node is the node that communicates directly with the PC. It is responsible for collecting the information received from all the reader nodes within the mesh network and forwarding this information to the PC. The Mesh Network is made up of reader nodes, the PC reader and the RFID tag. The synapse RF engines support this mesh networking right out of the box. The mesh network allows each of the signal strengths recorded by the reader nodes to be forwarded to the PC reader and ultimately to the PC. A desktop or laptop is needed to be set up with the PC reader and running the synapse portal software to allow the PC to accept the information from the mesh network. Once the PC receives the signal strengths, it forwards the posts the data to a database using HTTP protocol. The MySQL database is responsible for storing all the tracking information collected from the mesh network. The user using the Web Portal can then access this information. Finally, the Web Portal is a HTML 5 application using various web-based technologies such as JavaScript, JQuery and PHP. This is responsible for reading and interpreting the location co-ordinates from the database and showing the user where the RFID tag is in relation to the defined perimeters. The tag, reader nodes and PC reader all use synapse RF100 engines that can be programmed with python scripts. The scripts are sent over the air and onto the chips using the synapse portal software. The RF100 datasheet has all the technical information such as the maximum voltage and the maximum signal strength. It also has this table detailing the function of each pin which needs to be taken into account when designing the python scripts.

The Tag is mobile and the power pins of the RF100 engine are soldered to a 3 Volt power supply which is a battery pack enclosure that houses 2 AAA batteries (1.5V each). The tag has a 3mm LED that is connected to pin 14 (positive) and pin 16 (negative) which is initially off and will blink when the tag sends the signal. The reader nodes are stationary in a fixed position and powered by the mains. They use a 3V DC adapter. The DC adapter plugs into a 2.1mm Jack which is soldered onto the reader nodes RF100 power pins (21 and 24). The reader nodes also have a 5mm LED that is connected to pin 14 (positive) and pin 16 (negative). The LED is always on which indicates if the Nodes are receiving power and when they receive a signal they will blink. Once the nodes receive a ping from the tag, they must forward the signal and the node address to the PC reader. The PC Reader plugs into the PC's USB port by combining the RF 100 engine with a Synapse SnapStick. This allows the RF 100 to be powered by the PC and also allows it to pass data to the USB/COM ports. The PC reader listens for data being forwarded by the reader nodes, the data contains the tags address and signal strength and the readers address. The PC reader then sends this data to the USB port that it is plugged into. The tracking portal supports the ability to upload new maps and floor plans. For tracking people or assets the map (Figure 1) can be designed to reflect where the individual nodes are physically positioned. Each of the four physical nodes here has a different color of LED to allow the node to be identified easily. The map has a colored square for each node that corresponds to the physical nodes LED color and the middle of each square has the node address printed in the center. The reader nodes are represented by brown colored squares on the map and the tag is a colored circle. Ideally the tag (white circle) in the portal map will move towards the node as the physical tag moves towards the physical reader node.

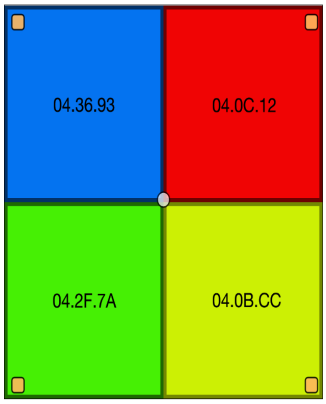


Figure 1 : Portal map proportional to the physical area bound by the reader nodes.

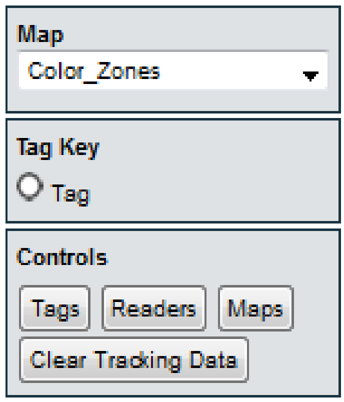


Figure 2: The design for the portals controls

The portal has a number of controls. It allows the user to select between maps if more than one is available. This caters for situations where multiple maps would be necessary e.g. tracking in a multi-story building. The portal also has a tag key that shows the color and identity of any tags within the tag database. Finally it contains buttons that opens forms that allow readers, maps and tags to details to be add/edited or deleted. The last button is the button that clears all tracking data; this will delete all tracking records from the database (see Figure 2). The portals 3 button controls (Tags, Readers, Maps) link to 3 management pages that allow details to be add/edit/delete. The portal is linked to a MySQL database. There are a number of tables including one called reader which holds all the information for the positioning (x and y coords) and identification (address) of the nodes on the map/floor plan (map_id). There is also a table to hold the information of the tag which will store the address and name of the tag. The preferred colour is also stored this will change the colour of the tag on the map. The position of the tag (x and y coords) are stored in the position table and this table is associated with the tag table and map table. The portal enables multi maps and floor plans to be uploaded therefore it is necessary to have a table for maps which will store each of the maps/floor plans and link all of the tables relationally.

III. 2D TRILATERATION ALGORITHM

To allow the tag to be tracked and displayed in the correct position, we designed an algorithm to calculate the position of the tag within a set area using 3 reader nodes and display the location correctly on a 2D map. This method assumes the nodes are arranged in square-like fashion and are equally spaced. Our 2D Trilateration algorithm has 8 steps:

Step 1: Calculate Signal to Distance & Pixel-Distance Ratio
Step 2: Calculate the Nearest and Adjacent Nodes
Step 3: Convert Signal Values to Distances
Step 4: Calculate Area of Width Triangle and Height Triangle
Step 5: Calculate Area of Width & Height of Rectangle
Step 6: Calculate Unknown sides of Rectangles from Areas
Step 7: Convert Width and Height to Pixel Points
Step 8: Calculate True direction and Coordinates on Map

To calculate the signal to distance ratio a maximum and minimum signal must first be identified. The difference must then be calculated by taking the maximum away from the minimum:

$$\text{max\_min\_signal\_difference(dBm)} = \text{max\_signal(dBm)} - \text{min\_signal(dBm)}$$

The distance in meters between the nodes is then divided by the max_min_signal_difference to achieve the signal to distance ratio:

$$\text{signal\_to\_distance\_ratio(m per dBm)} = \frac{\text{node\_distance\_metres(m)}}{\text{max\_min\_signal\_difference(dBm)}}$$

To calculate the pixel to distance ratio, the physical distance (m) between the node must be divided by the virtual distance(px):

$$\text{pixel\_to\_distance\_ratio(px per m)} = \frac{\text{node\_distance\_pixels(px)}}{\text{node\_distance\_metres(m)}}$$

The nearest node will always be the one with the lowest signal and the adjacent nodes can be identified by analyzing the x and y coordinates of the nearest node. The adjacent node that will affect the tags x-coordinate will have the same x-coordinate as the nearest node and will have a different y-coordinate as the nearest node. The opposite conditions identify the adjacent node that will affect the tags y-coordinate as this node will have the same y-coordinate as the nearest node and will have a different x-coordinate as the nearest node. Take the signal values from the nearest and adjacent nodes and convert them into distances using the signal_to_distance_ratio. The area of the triangle can be found using Heron's Formula, where a, b, c are the length of the sides of the triangle:

$$Area\ Of\ Triangle = \sqrt{P(P-a)(P-b)(P-c)}$$

P in this formula is the perimeter of the triangle, which is found by:

$$Perimeter = \frac{a+b+c}{2}$$

The area of the width triangle uses the distances obtained between the closest node, the tag and the adjacent node(that will affect the x-coordinates of the tag). The area of the height triangle uses the distances obtained between the closest node, the tag and the adjacent node(that will affect the y-coordinates of the tag). The area of the width rectangle and height rectangle can be found by multiplying the area of the width triangle and area of the height triangle by 2 respectively.

$$Area\ of\ Rectangle = Area\ of\ Triangle \times 2$$

The unknown sides can then be discovered by dividing the area of the rectangle by the known side to get the value of the unknown side. The unknown side of the width rectangle will be the distance in meters the tag is from the left or right side of the tracking area (square) depending on which nodes are used. The unknown side of the height rectangle will be the distance in meters the tag is from the top or bottom side of the tracking area (square) depending on which nodes are used.

$$Unknown\ side\ of\ Rectangle = \frac{Area\ of\ Rectangle}{Known\ side}$$

We converted the unknown side of the width rectangle (tag x-coordinate) and the unknown side of the height rectangle (tag y-coordinate) to pixels by multiplying them by the pixel_to_distance_ratio. The tag can now be represented on a 2D Map using the boundaries of the nodes and the X and Y coordinates obtained.

IV. TESTING

The testing includes the benchmark and distance testing of the RF 100 engines to find the optimum range that the nodes can be apart. This was to benchmark the best distance for the nodes to be placed apart for the most accurate signal results. This test data was achieved using the synapse portal on a laptop with a synapse SnapStick acting as a bridge to receive the link quality (signal strength) from the reader node plugged in at the end of the hall way.

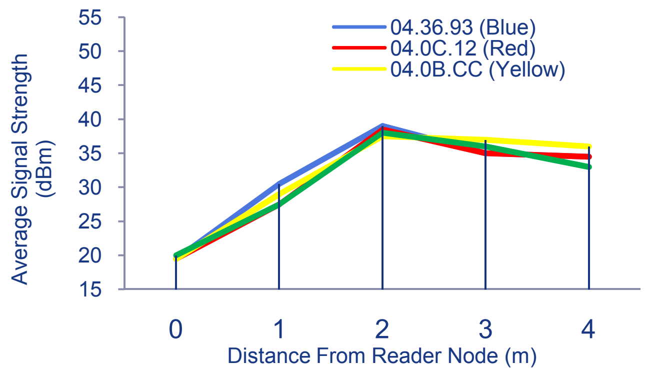


Figure 3: Signal strengths received from different distances from the node

Reader Node	Distance (m)	Link Quality (dBm)	Link Quality (dBm)
04.36.93 (Blue)	0	19 – 20	19.5
	1	28 - 33	30.5
	2	37 - 41	39
	3	33 - 37	35
	4	33 - 36	34.5
04.0C.12 (Red)	0	19 - 20	19.5
	1	26 - 29	27.5
	2	37 – 40	38.5
	3	34 – 36	35
	4	33 - 36	34.5
04.2F.7A (Green)	0	19 - 21	20
	1	26 - 29	27.5
	2	37 - 39	38
	3	35 - 37	36
	4	32 - 35	33
04.0B.CC (Yellow)	0	19 - 20	19.5
	1	28 - 30	29
	2	36 - 39	37.5
	3	36 - 38	37
	4	35 - 37	36

Table 1: No Tag – Signal strength of each node

The reader node was stationary and the laptop was moved from the reader node at a distance of 1 meter at a time. The raw data is in Figure 3 for a higher level comparison of the signal strength to distance results of each of the reader nodes.

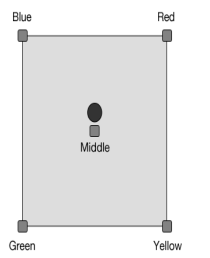
Reader Nodes with signal strengths received (dBm)					Position of Tag
	Blue	Red	Yellow	Green	
Test 1	53	52	**43**	52	
Test 2	45	49	46	**40**	
Test 3	**43**	52	46	44	
Test 4	**40**	43	**40**	46	
Test 5	**41**	46	44	**41**	
Min - Max	40 - 53	43 - 52	40 - 46	40 - 52	
Average	44.4	48.4	43.8	44.6	

Figure 4: Testing from the middle position of the 2m x 2m square

Figure 5: Key for diagrams for position of tag

We present data collected the first time the tracking system and physical tracking area was set up. The tag was placed in 5 different set locations multiple times to allow the signal data to be recorded, an average to be calculated and signal fluctuations to be analysed. This data was used when designing the tracking algorithm and developing our grouping solution to improve data consistency and minimize fluctuations. The tag was positioned in the middle of the 2m x 2m tracking area and 5 sample signals (Tests 1 - 5) were taken and recorded in a table (Figure 4). The average of each node was taken and the maximum and minimum boundaries were also recorded. The tag was positioned beside the blue node within the 2m x 2m tracking area and 5 sample signals (Tests 1 - 5) were taken and recorded in a table (Figure 6). The average of each of the nodes was taken and the maximum and minimum boundaries were also recorded.

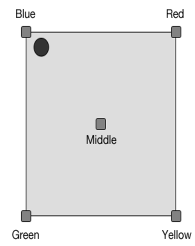
Reader Nodes with signal strengths received (dBm)					Position of Tag
	Blue	Red	Yellow	Green	
Test 1	**37**	53	56	51	
Test 2	**33**	46	56	41	
Test 3	**39**	49	50	48	
Test 4	**28**	47	43	35	
Test 5	**32**	57	49	47	
Min - Max	28 - 39	46 - 57	43 - 56	35 - 51	
Average	33.8	50.4	50.8	44.4	

Figure 6: Testing from the position of the blue node in the 2m x 2m square

The tag was positioned right beside the green node within the physical 2m x 2m tracking area and 5 sample signals (Tests 1 - 5) were taken and recorded in a table (Figure 6). The average of each of the nodes was taken and the maximum and minimum boundaries were also recorded.

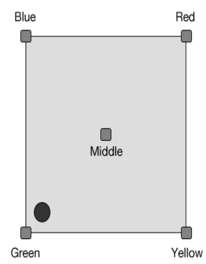
Reader Nodes with signal strengths received (dBm)					Position of Tag
	Blue	Red	Yellow	Green	
Test 1	38	53	39	**32**	
Test 2	51	55	61	**36**	
Test 3	42	49	45	**32**	
Test 4	57	45	46	**27**	
Test 5	61	55	46	**23**	
Min-Max	38 - 61	45 - 55	39 – 61	23 - 36	
Average	49.8	51.4	47.4	30	

Figure 7: Testing the position of the Green node in the 2m x 2m square

The tag was positioned beside yellow node within the 2m x 2m area and 5 samples (Tests 1 - 5) were taken (Figure 8).

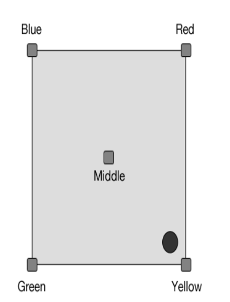
Reader Nodes with signal strengths received (dBm)					Position of Tag
	Blue	**Red**	**Yellow**	**Green**	
Test 1	66	51	**35**	39	
Test 2	52	55	**42**	45	
Test 3	55	48	**39**	46	
Test 4	46	45	**36**	43	
Test 5	54	51	**36**	46	
Min-Max	46 - 66	45 - 55	35 - 42	39 - 46	
Average	54.6	50	37.6	43.8	

Figure 8: Testing from the position of the Yellow node in 2m x 2m square

The tag was positioned beside the red node within the 2m x 2m area and 5 samples (Tests 1 - 5) were taken (Figure 9).

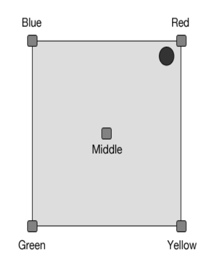
Reader Nodes with signal strengths received (dBm)					Position of Tag
	Blue	**Red**	**Yellow**	**Green**	
Test 1	38	**35**	43	43	
Test 2	40	**34**	43	44	
Test 3	47	**36**	44	51	
Test 4	64	**40**	47	49	
Test 5	53	**37**	55	46	
Min-Max	38 - 64	34 - 40	43 - 55	43 - 51	
Average	48.4	37.4	46.4	46.6	

Figure 9: Testing from the position of the Red node in 2m x 2m square

We found that the maximum distance the nodes could be placed apart from each other was 2 meters this assumption can be made because after 2 meters the signal starts to drop meaning the signal received would erroneous and inaccurate. This would have a strange effect on the tracking system as after 2 meters because of the signal dropping it would cause the system to think the tag/object was closer rather than further away from a node. For this reason the maximum physical tracking area was 2m by 2m. We have assumed that the distance constraint was down to hardware limitations; specifically the RF 100 engines power output and the fact that the RF engine that was used (RF100PC6) only had an F antenna. Many of synapses models allow antennas to be screwed on and also allow many different antennas to be used which could give a better and further reading. We believe that incorporating some of synapses other models of RF Engines will improve the range and precision of the hardware and system. The best performance and most accurate tracking data was recorded when the maximum signal was capped around 7dBm lower than the actual maximum signal recorded and the minimum signal was capped 5dBm higher than the actual minimum signal recorded.

VI. CONCLUSION

The homemade tracking system that was built during this project cost roughly around £200 UK Sterling. By building all of the software and hardware components it meant that a substantial amount of savings were made. However, the time spent developing and building each component must be taken into account. The homemade tracking system built within this project has even better accuracy results and lower latency times than many of the commercial applications. Most of the other solutions use Wi-Fi or a combination of Wi-Fi and RFID to track whereas the solution developed within this project has been purely RFID based. This means that the other systems do have a wider tracking range and the home made tracking system can only track within the areas where reader nodes are deployed. Because the homemade tracking system has been developed from scratch it does not have any software support.

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