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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**NETWORK LOCALIZATION FOR UNMANNED ROBOTICS
SYSTEMS USING THE RECEIVED SIGNAL STRENGTH
INDICATOR**

A thesis submitted in partial satisfaction of the
requirements for the degree of

Master of Science

in

COMPUTER ENGINEERING

by

Sina Kahnemouyi

June 2016

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Abstract

Network Localization for Unmanned Robotics Systems Using the Received Signal Strength Indicator

by

Sina Kahnemouyi

This thesis presents a preliminary investigation of a localization methodology which does not depend on signals from the Global Positioning System (GPS). Instead, the Received Signal Strength Indicator (RSSI) between several stationary nodes (anchor nodes) and a mobile node to predict the position of the mobile node. The main goals of the thesis are to find the optimal localization algorithm and to identify the optimal number of anchor nodes that would provide the desired localization precision. We will show that the proposed technique is affordable and can be successfully used in electronically noisy environments (e.g., indoors). The technology used is a 434 MHz RF localization system that should provide less interference than the typical 2.4 GHz systems that commonly experience interference from other domestic technologies. The results reveal the feasibility and shortcomings of these systems for creating a more accurate real-time positioning system.

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Chapter 1

Introduction

Wireless localization systems are used widely in indoor public places such as libraries and schools to help people navigate to their indoor destinations. However, as a result of continuously growing interest in developing autonomously navigating Unmanned Robotic Systems (URS) (e.g., Unmanned Aerial Vehicles) that should be able to navigate in GPS-denied environments (e.g., indoor navigation) wireless localization has become a topic of extensive research[1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. New work on such systems has been simulated by recent developments of small and affordable transceiver units that could be easily fitted on-board of autonomously navigating robots.

One of the goals of this work is to narrow the gap between outdoor (GPS accuracy) and indoor navigation. Most of the indoor localization techniques use either the IEEE 802.15.4 (ZigBee) [22] or IEEE 802.11 (Wireless LAN)[8, 20, 23]. However, since these protocols mainly operate in the 2.4 GHz range, they suffer interference from

many other domestic wireless devices on the same frequency band such as WLAN access points (e.g., microwave ovens, cordless phones, and Bluetooth devices). To overcome this issue, We chose a different frequency band to implement our localization system.

We envision that this work can be expanded to 1) operate robots or Unmanned Aerial Vehicles indoors or in an urban environments where the GPS signal fidelity is low, or 2) operate in a coordinated formation independent of external localization techniques. The effective range of 200 meters for each of the wireless nodes in our system can possibly allow small UAVs to take advantage of this platform for autonomous indoor navigation. Similarly, autonomous rovers can navigate accurately, and therefore, be used to scan indoor areas and map the environment.

Numerous studies have been done on localization techniques using RSSI (Received Signal Strength Indication). These papers examine different wireless physical layer protocols such as Bluetooth, Wi-Fi and ZigBee. Although most of these studies acknowledge that RSSI is not the most reliable means of localization, RSSI does provide an affordable and feasible method for indoor navigation.

Chapter 2

RF localization methods

There are several RF-based methods that can provide indoor localization.

- RSSI based
- Angle of Arrival(AoA)
- Time of Arrival (ToA)/Time of Flight (ToF)
- Time Difference of Arrival (TDoA)

In this thesis we investigate the RSSI based method. To find the relationship between RSSI values and the distance from the mobile node to the stationary node, a regression model is constructed and used to calibrate the RSSI values at multiple pre-determined locations. There are many methods, based on path loss, to find the location using RSSI values or calculated distances[8].

The Angle of Arrival (AoA) method uses the angle of arrival of the target signal coming from a known position to multiple stationary nodes[7]. Indoors the AOA

technique is affected by multipath and Non-Line of Sight (NLOS) signals, along with reflections from various objects like doors or ceiling which makes it non-ideal for indoor implementation. These factors can alter the direction of the received signal and consequently degrade the accuracy of the AOA-based positioning system [9].

The Time of Arrival (ToA) technique depends on the accurate synchronization of the arrival time of a signal transmitted from a target device to several base stations. In ToA, the mobile device broadcasts a time stamped signal towards the other nodes in the system. When the message is received, using the transmission delay and the speed of the signal, the distance between the mobile node and the receiving node is calculated. [10]. Although this method provides the highest accuracy, one of the disadvantages of the ToA method is that all the systems must have a synchronized clock, as any delays in the system causes inaccuracies which renders the cost of devices relatively high.

The Time Difference of Arrival (TDoA) is measured between several sample points with known positions and use relative time at each stationary node instead of absolute time measurements. Unlike the ToA, the TDoA does not require a synchronized time-of-transmission to resolve the timestamps and estimate the location of the mobile node. In TDoA, a signal with an unknown starting time is received at various stationary nodes and only the receivers require synchronization[11].The cost of the system has been relatively high; however, in the past few years there have been less expensive systems emerging with this capability. Our future work would possibly rely on this method.

2.1 RF RSSI Based Localization

The RF RSSI-based localization method warrants expanded review to appropriately justify our decision not to use the more standard Bluetooth, Wi-Fi, or ZigBee modules that are commercially available.

2.1.1 Bluetooth

The amount of research done on Bluetooth localization is relatively small. This is most likely due to the short functional range of Bluetooth prior to the release of Bluetooth 4.0. Also, the previous versions of this protocol were substantially less power efficient and were therefore not a very competitive solution when compared to the other technologies that were already available. However, as Bluetooth 4.0 was released, most of these issues were addressed and more promising results were produced. Berreria, *et. al.*[5] were able to achieve a localization accuracy of 1.5 meters using Bluetooth received signal strength, while investigating collaborative localization of mobile devices.

Also, similar to other technologies, the raw Bluetooth RSSI values can not be reliably used and a low pass filter is needed for the values to be practical for most localization applications [2]. In addition, in a slave and master Bluetooth connection, since all slaves have to be paired with the master device, as the number of slaves increases over a certain number the connection can become slow and unreliable.

2.1.2 Wi-Fi

Modern WiFi access points come with dual frequency options of 2.4 GHz and 5 GHz. Although complex measures have been taken to reduce the amount of interferences created by other 2.4 GHz devices, this type of interference still exists due to the heavy use of access points in this frequency range. In case of the RSSI, small amounts of interference cause significant errors in estimating the position of a node in such systems. The 5 GHz frequency WiFi devices are currently less prone to interferences from other devices due to the smaller number of access points in this frequency range. In places where lots of other WiFi modules are used[25]; however, with the increasing popularity of 5 GHz devices, this may not be the case in the near future.

Biswas and Veloso[12] developed a WiFi localization system for a robotic platform by implementing the Monte Carlo Localization with Bayesian Filtering and multitude of stationary nodes to a mean error of 0.7 meters. However, with 5 access points, the average localization error was estimated at more than 2 meters. In work by *Seshadri et. al.* [26] it was found that using particle filtering in a residential-like establishment they were able to get a localization error converging to just above two meters as well.

2.1.3 ZigBee

Researchers have been able to achieve an accuracy of 1.5-2m using ZigBee devices implementing the maximum likelihood estimation through the least squares method to find the target's position[13]. ZigBee Localization Algorithm (ZiLA) has been also cross validated against the maximum likelihood and was able to achieve a 1.8

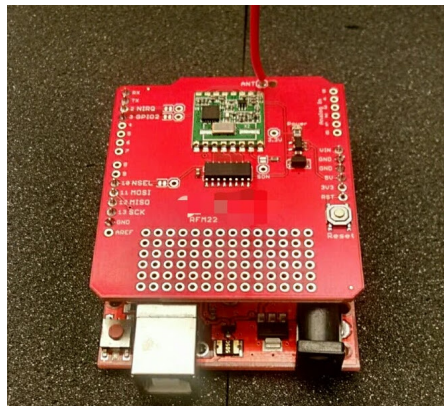
meter accuracy, in a grid of 16 anchor nodes, each one meter apart [14]. Using the same 2.4 GHz frequency as WiFi makes this method also vulnerable to RF interference from all the other 2.4 GHz devices including WiFi. In both Zigbee and WiFi, measures have been taken to reduce these kinds of RF interference; however, these measures mostly focus on delivery of uncorrupted signals, and the signal strength may still be affected.

2.2 Thesis Organization

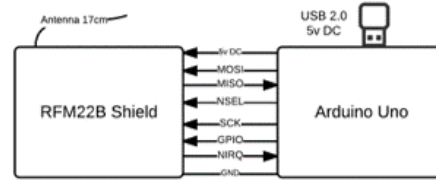
The thesis is organized as follows: Section II presents the hardware used for the experiments; Section III presents the localization approach; Section IV presents the results from testing and Section V presents the conclusions and future work.

2.3 Proposed Hardware

In this research, we used the RFM22B-S2 module which is a 434 MHz radio transceiver. Because of the relatively low transmitting frequency of our radio modules, we used a 17.3 cm conductor as a quarter-wave-length monopole antenna. However, we were unable to disable the on board antenna which emitted a directional signal that could contribute to the error that we found during our experiments. Figure 2.1 illustrates an image of a wireless node and its block diagram. The communication between the modules and the microcontrollers (REIK Uno R3, an Arduino Uno compatible device) was done by Serial Peripheral Interface (SPI). The nodes are powered through USB and a RFM22 Shield was used to route the connectors to the microcontroller board. The



(a) RFM22B-S2 Radio Module connected to the microcontroller board



(b) Connections and electrical block diagram of each node

Figure 2.1: Hardware configuration

units are powered using batteries through USB2.0 protocol devices (except for anchor 1 which receives its power from a computer's USB2.0 port).

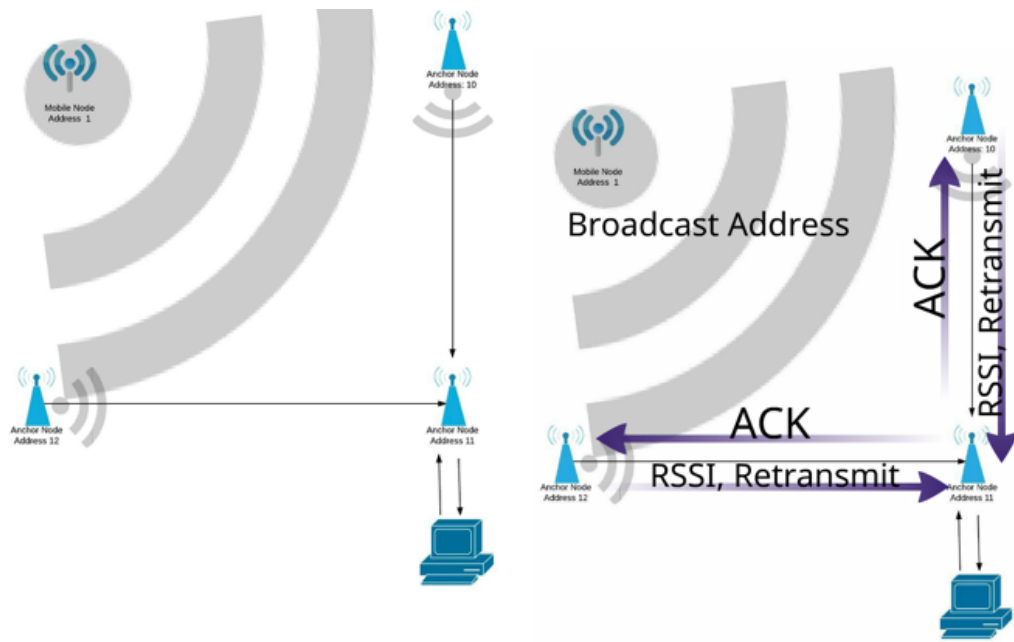
One of the advantages of this combination of modules is that both of the main components of each node (Arduino UNO and RFM22B Shield) are readily available for purchase at a relatively low cost. In addition, the RFM22B shield is completely compatible with Arduino UNO and does not require any additional modifications to integrate. Because of the low frequency of the RFM22B transceiver, there is no need for a complex antenna, and a simple monopole antenna (18 AWG wire) would suffice. Also, the open source RadioHead library for RFM22B is completely compatible with our version of Arduino and makes the programming of the system particularly easy with high level API functions such as send and receive, in addition to more options for configuring more complex networks and datagrams [24].

Chapter 3

Localization Approach

3.1 RF Node System and Relationships

Our RF localization system consists of at least 3 stationary nodes as wireless beacons (Anchor nodes), in addition to one or more wireless mobile nodes (Tag nodes). This system can find the approximate location of the mobile nodes given that position of the stationary nodes are known to the system beforehand, and the tag node is within the wireless range of all of the stationary nodes. The mobile nodes broadcast a wireless beam, which all the stationary nodes receive. The received information which includes the Received Signal Strength Identification (RSSI) is then used by the computer to calculate the location of the mobile nodes and present them to the user. In the system illustrated in Figure 3.1a we set one of the stationary nodes as the main anchor to which all the other stationary nodes send their data. After the main server receives all the information, it does not compute the position by itself, but rather sends



(a) The information collected by each anchor node is gathered in the main anchor and transferred to the client computer to compute the position of the mobile node

(b) Reliable communication between the main anchor and the two other anchors ensures the delivery of the packets

Figure 3.1: Communications between anchors

the information, using a serial communication (USB Cable), to the client computer to compute the mobile node positions and present the position to the client in a Graphic User Interface (GUI). If the GUI is not desired then all of the processing can be done on the nodes without the client computer.

3.2 Reliable Anchor Datagram Communication

The chosen wireless relationship between the anchor nodes, although efficient, had its own complexities that had to be considered. In a wireless system in which anchor nodes are constantly communicating with each other, transmitting the received information of potentially hundreds of mobile nodes, collisions are likely to occur. Therefore, a system of reliable datagram communication, illustrated in Figure 2.3.1b, was implemented to ensure the delivery of each message by defining addressed datagrams with acknowledgments and retransmissions. In this system, flags and sequence numbers are added to datagrams to make them reliable in the sense that messages are acknowledged by the recipient, and unacknowledged messages are retransmitted until acknowledged or retries are exhausted[24].

3.2.1 Transmission and Receipt Process

When an addressed message is sent, the sender will wait for an acknowledgment packet, and retransmit after the timeout for the maximum number of retries. The retransmit timeout is randomly varied between a set timeout and double that value to prevent collisions on all retries when two nodes happen to start transmitting at the

same time. This method is also recognized as pure ALOHA[24].

On the receiver side, when an addressed message is collected by the application, an acknowledgment is automatically sent to the sender. Each sent message also includes a sequence number (ID), which helps both nodes to recognize packets for acknowledgment or retransmission in case multiple messages are sent at the same time.

However, as more anchors are added to the system, the main anchor is responsible for sending back more acknowledgment messages. We noticed that some of the acknowledgments were not sent or received in the system because of possible signal collisions which resulted in more delays in the system's overall sample rate. To solve this problem, we designed a system in which the anchor nodes would send their information to the main anchor node in a timely fashion each with an incremented delay different than the other anchor nodes. This eventually decreased the number of collisions and eliminated the unnecessary delays caused by them.

3.2.2 Broadcast Messages

Unlike the communication among the anchor nodes, the communication between the mobile nodes and the anchor nodes does not need the confirmation of delivery. Also, each mobile node needs to transmit to all the anchor nodes at the same time. Each mobile node could possibly transmit individual messages to the address of each of the anchor nodes; however, this causes unnecessary delays between each transmission. Instead, each mobile node transmits its own address to a broadcast address which all anchor nodes recognize in addition to their own distinct addresses. This way, only one

2 Bytes		
Mobile Nodes	Anchors	Broadcast
0x00 - 0xFA	0xFB-0xFE	0xFF

Figure 3.2: 2 byte addressing scheme for each node

transmitted message is received by all anchors with very small receipt time differences.

3.2.3 Frames and Headers

The RFM22B hardware module supports the transmission and reception of 255 bytes at a time. However, for these frames to be sent and received properly, headers are added to the messages transmitted. Each message sent and received by the RF module drive includes 4 headers:

- **TO** The node address that the message is being sent to (broadcast RH BROADCAST ADDRESS (255) is permitted)
- **FROM** The node address of the sending node
- **ID** A message ID, distinct (over short time scales) for each message sent by a particular node
- **FLAGS** a bitmask of flags. 8 bits are for applications.

Each of the bits in the flag byte can be set for a different purpose. For instance, setting the least significant bit indicates an acknowledgement frame and indicates that the frame does not include data to follow.

3.3 Addressing

A two-byte addressing system is used for all nodes in the system. This provides a maximum of 256 addressed node (0x0 to 0xFF). Although the system only has 3 anchor nodes, 4 addresses are reserved for the anchor nodes in case a 4th anchor is added in the future for 3D localization. Address 0xFF is reserved for broadcast messages. This leaves 251 nodes available for potential mobile nodes. Figure 3.2 illustrates how the 2 byte address space is divided for the described purposes.

3.4 Localization Calculations

To calculate the coordinates of the mobile nodes, We used two different methods. The first is the intersecting circle trilateration method[19] and the second is a simple linearized model of the combined system. The two methods both, yield viable solutions to the localization problem, however the linearized model is readily expandable to more than three anchor nodes.

3.4.1 Free Space Path Loss (FSPL)

The Free Space Path Loss (FSPL) principle is a fundamental component of any RSSI localization technique. FSPL is the signal attenuation of a wave in a medium (dry air for our uses). There are some limitations to the use of FSPL, for example in order to get good results the RF modules are required to have lines of sight with each other to avoid RF reflections and diffraction[18]. Some additional factors that can affect

the calculation of the distance via FSPL are as follows:

- reflection on metallic objects
- superposition of electromagnetic fields
- diffraction on edges
- refraction by items with different propagation velocity
- polarization of electromagnetic wave [17, 21]

FSPL can be calculated as follows[19]:

$$FSPL(dB) = 10 \log \left(\frac{4\pi df}{c} \right)^2 \quad (3.1)$$

where c is the speed of light, f is frequency and d is the distance. With the speed of light and the broadcast frequency of 434 MHz can be inserted in 3.1 and solved for the distance, resulting in :

$$d = 10^{\frac{|FSPL|-25.2}{20}} \quad (3.2)$$

Where the FSPL is the difference between broadcasted and received signal.

$$FSPL = B_{dB} - R_{dB} \quad (3.3)$$

3.4.2 Intersecting Circles Trilateration Calculation

The intersecting circles trilateration algorithm[19] was implemented for this thesis. This method assumes that the mobile node is receiving the distance information from each anchor node (presuming the anchor node positions are known). Assuming

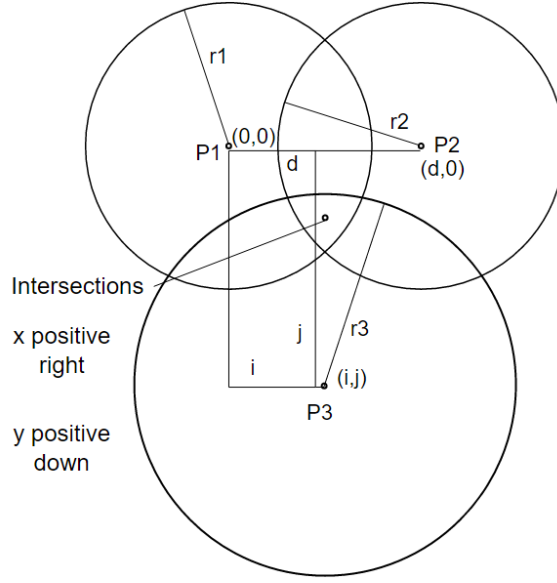


Figure 3.3: Coinciding circles that represent the radio signal strength of the nodes in 2 dimensions [27]

that the RF signal radiates uniformly (and is attenuated uniformly), each anchor node's radius indicates the distance it has from the mobile node. By calculating the intersection of the three circles, we calculate the position of the mobile node.

The position of the mobile node can be calculated where the three distances intersect. Figure 3.3 illustrates the scheme of the interceptions.

$$r_1^2 = x_m^2 + y_m^2 \quad (3.4)$$

$$r_2^2 = (x_m - d)^2 + y_m^2 \quad (3.5)$$

$$r_3^2 = (x_m - i)^2 + (y_m - j)^2 \quad (3.6)$$

From 3.4 and 3.5 we have:

$$r_1^2 - r_2^2 - r_3^2 = x_m^2 - (x_m - d)^2 - (x_m - i)^2 + (y_m - j)^2 \quad (3.7)$$

solving for x_m and y_m we have:

To calculate the x component of the mobile node's coordinate, we divide equation 3.8 by equation 3.9.

$$f = ((d_1^2 - d_2^2) + (i_2^2 - i_1^2) + (j_2^2 - j_1^2)) (2j_3 - 2j_2) ((d_2^2 - d_3^2) + (i_3^2 - i_2^2) + (j_3^2 - j_2^2)) (2j_2 - 2j_1) \quad (3.8)$$

$$g = ((2i_2 - 2i_3)(2j_2 - 2j_1) - (2i_1 - 2i_2)(2j_3 - 2j_2)) \quad (3.9)$$

$$x_m = \frac{f}{g} \quad (3.10)$$

and the y component can be calculated by:

$$y_m = \frac{((d_1^2 - d_2^2) + (i_2^2 - i_1^2) + (j_2^2 - j_1^2) + x(2i_1 - 2i_2))}{(2j_2 - 2j_1)} \quad (3.11)$$

3.4.3 Linearization and Calibration

In order to do the calibration of the system we assume that the RSSI is linearly related to the received signal strength, represented in equation 3.12

$$R_{dB} = aRSSI - b \quad (3.12)$$

where a and b are the linear coefficients that result from least squares calibration. Figure 3.4 the result of the calibrations and examples of the fitted lines for three anchor nodes that were used for the calibration. by substituting 3.12 into 3.3 and 3.2 we get:

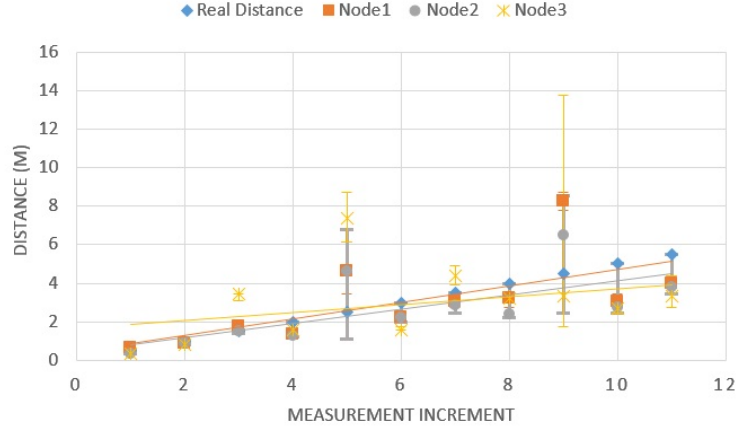


Figure 3.4: The error in calculating the distance using RSSI values compared to the actual position.

$$aRSSI_i + b = B_{dB} - 20\log_{10}\sqrt{(x_m - x_i)^2 + (y_m - y_i)^2} - 25.2 \quad (3.13)$$

where x_i and y_i are the x and y coordinates of the i^{th} anchor node respectively and x_m and y_m are the coordinates for the mobile node. The linearization can be done via a first order Taylor expansion resulting in:

$$RSSI_i = \frac{1}{a} \left(B_{dB} - 20\log_{10}\sqrt{(x_m(t_0) - x_i)^2 + (y_m(t_0) - y_i)^2} - 25.2 - b + \frac{-20\log_{10}\sqrt{(x_m(t_0) - x_i)^2 + (y_m(t_0) - y_i)^2}}{dxdy} \begin{bmatrix} x_m - x_m(t_0) \\ y_m - y_m(t_0) \end{bmatrix} \right) \quad (3.14)$$

where $x_m(t_0)$ and $y_m(t_0)$ are the mobile node coordinates to be linearized about. It is assumed that the initial condition is known and that the the system will be linearized about the initial condition. Including all of the anchor nodes results in a system of equations that can be represented by:

$$RSSI \approx A \begin{bmatrix} x_m \\ y_m \end{bmatrix} + BD_{dB} + C \quad (3.15)$$

where,

$$A = \begin{bmatrix} \frac{-10}{a_1} \frac{2(x_m(t_0)-x_1)}{(x_m(t_0)-x_1)^2+(y_m(t_0)-y_1)^2} & \frac{-10}{a_1} \frac{2(y_m(t_0)-y_1)}{(x_m(t_0)-x_1)^2+(y_m(t_0)-y_1)^2} \\ \vdots & \vdots \\ \frac{-10}{a_n} \frac{2(x_m(t_0)-x_n)}{(x_m(t_0)-x_n)^2+(y_m(t_0)-y_n)^2} & \frac{-10}{a_n} \frac{2(y_m(t_0)-y_n)}{(x_m(t_0)-x_n)^2+(y_m(t_0)-y_n)^2} \end{bmatrix} \begin{bmatrix} x_m \\ y_m \end{bmatrix} \quad (3.16)$$

$$B = \begin{bmatrix} \frac{1}{a_1} \\ \vdots \\ \frac{1}{a_n} \end{bmatrix} \quad (3.17)$$

$$C = \begin{bmatrix} \frac{1}{a_1} (-20 \log_{10} \sqrt{(x_m(t_0) - x_1)^2 + (y_m(t_0) - y_1)^2} - 25.5 - b_1) \\ \vdots \\ \frac{1}{a_n} (-20 \log_{10} \sqrt{(x_m(t_0) - x_n)^2 + (y_m(t_0) - y_n)^2} - 25.5 - b_n) \end{bmatrix} \quad (3.18)$$

where n is the number of nodes. Equation 3.15 can be solved to give the mobile node location.

Chapter 4

Results

The experiments were performed in the engineering building at the University of California, Santa Cruz. No attempts were made to isolate the system from the building's WiFi, climate control or other electronics. We believe that this represents a realistic environment with the expected interferences and disturbances. The testing area was a triangle of 16.3 m^2 where all anchor nodes were in each other's line of sight with no objects in between.

4.1 Intersecting Circles Trilateration

With 3 anchor nodes we collected the data for 11 distinct positions. Each of which were positioned within the confinement of a triangle-shaped area surrounded by our anchors. We collected RSSI measurements at each position for 20 seconds with a sample rate of 1 hertz. Our average error rate for the x and y were 0.81m and 1.03m respectively. The absolute distance error was 1.31m all of which can be seen in Table

4.1 along with the maximum and minimum errors.

Table 4.1: Errors in the intersecting circles trilateration method

	x	y	distance
Mean Error	0.81	1.03	1.31
Max Error	1.33	2.81	3.11
Min Error	0.14	0.05	0.15

Figure 4.1 illustrates the result where the colored triangles are the actual mobile node position and the circles are the average calculated position, each pair is colored differently for each sampling location. There are error bars for each calculated position to show the maximum and minimum sample values during the 20 seconds in the x and y directions. We can see that there is a very large range of possible values and that this method has a relatively low precision. It is also worth noting that the ranges are directional specific with the y direction having a much larger measured range.

4.2 Linearized Model Results

4.2.1 Three Anchor Nodes

Using the same number and location of anchor nodes as in the previous experiment, the linearized model was instead used to calculate the relative position of the mobile node. Figure 4.2 shows the actual and calculated positions in the same manner as the previous plot. The actual positions are represented by triangles and

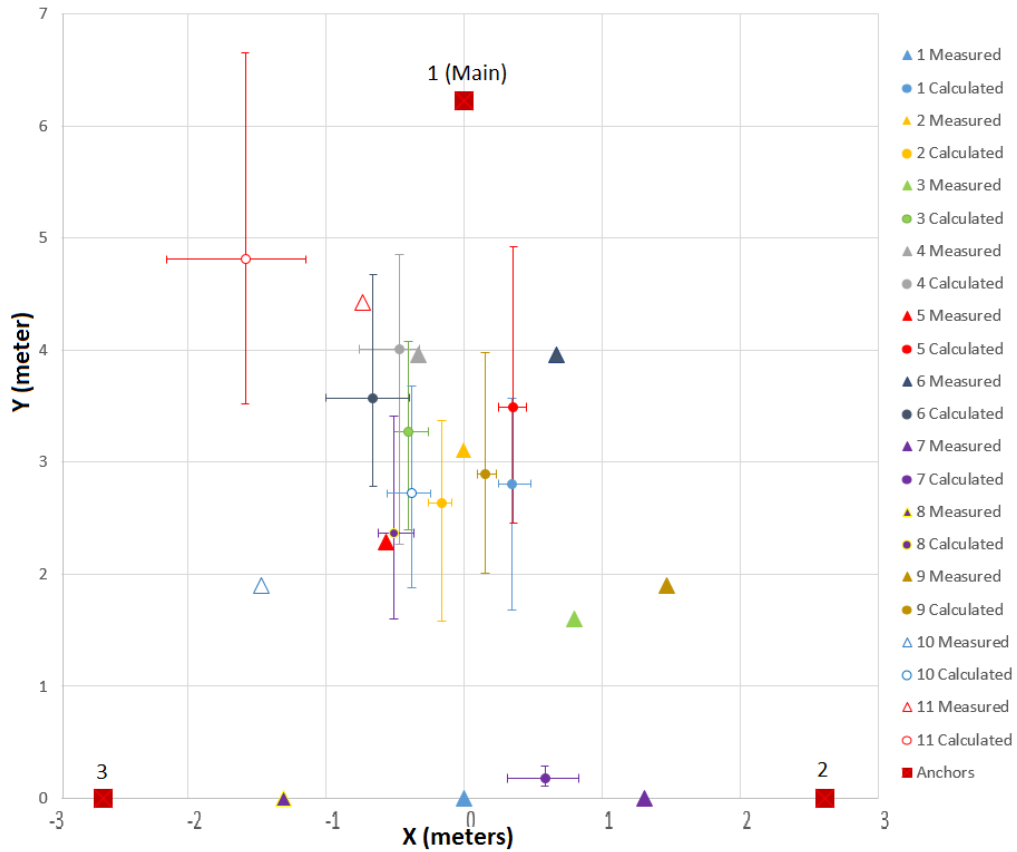


Figure 4.1: Intersecting circles localization. The error bars indicates the deviation of the data at each point

the calculated positions by the circles with the error bars indicating the maximum and minimum calculated values. We can see that error bars are much smaller in Figure 4.2 than in Figure 4.1, suggesting that the linearization method is much more precise than the intersecting circle trilateration method. This makes sense when looking at how each method works. The linearization results in a first order approximation where the noise is linearly related to the outputs while the trilateration method has the noise exponentially related to the position.

While Figure 4.2 shows that the linearized method is more precise, Table 4.2, shows that there is only a minor increase in accuracy for the linearized model with three nodes. It is important to note here that the linearization was performed at various points near the actual position but not the actual position itself. We saw small but noticeable effects on the selected linearization point until the linearization point was more than a meter away from the actual position. This could explain why we do not see more dramatic accuracy increases with the three node linearization.

Table 4.2: Errors in the 3 anchor linearized model

	x	y	distance
Mean Error	0.77	0.98	1.25
Max Error	1.34	2.10	2.49
Min Error	0.08	0.16	0.18

4.2.2 Four Anchor Nodes

With the addition of the fourth node the distance between the actual position and the calculated position continued to decrease. Figure 4.3 shows the fourth anchor placed on the right side between the apex node and the right base node. It would also appear that the placement of the node significantly aided in the precision in the y direction because its dramatic reduction was nearly 50%, while the x direction only gained approximately 12%. This suggests that the node placement is critical for directional accuracy. It should again be noted that for the sake of demonstration we chose

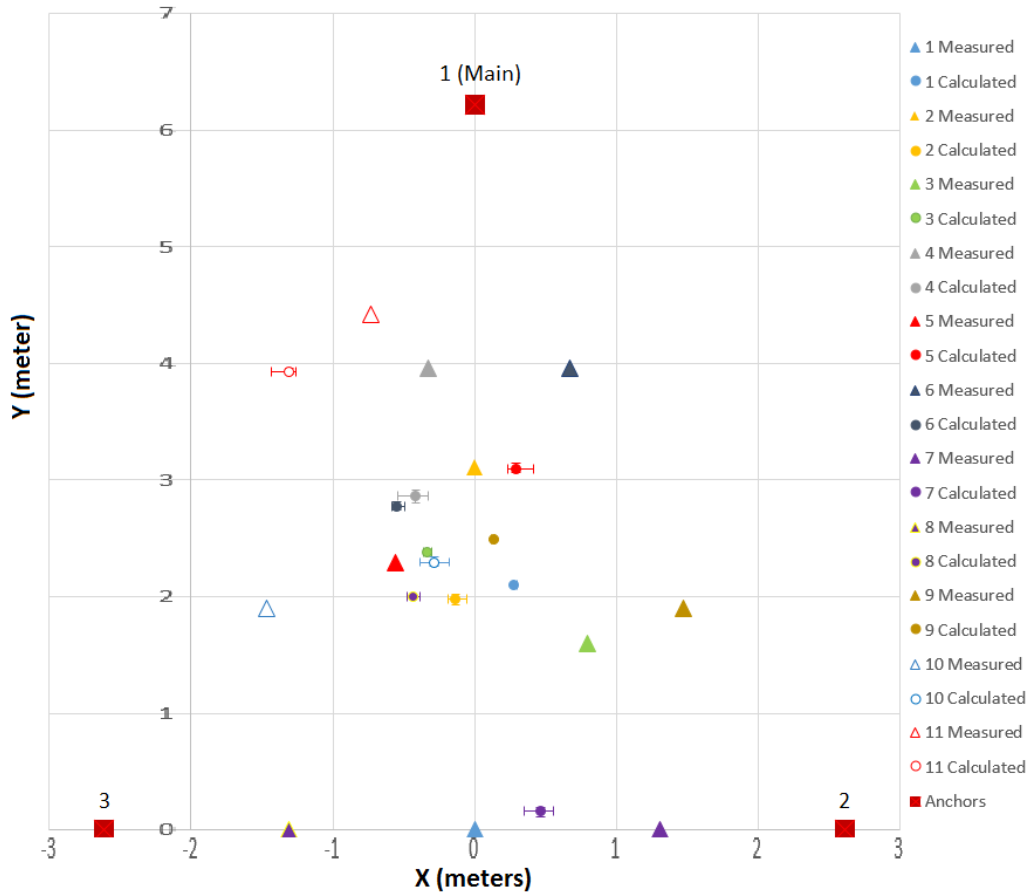


Figure 4.2: Linearized trilateration. The standard deviation has decreased significantly compared to the previous method. Error bars in x and y axes indicate the deviation of the calculated data

the actual position of the mobile nodes to linearize about for the four and five anchor experiments.

Comparing tables 4.3 and 4.2 indicates that the system with 4 anchor nodes was able to decrease the mean distance error from 1.25 to 0.81 meters. Moreover, the minimum and maximum errors of all the data that we collected during 20 seconds

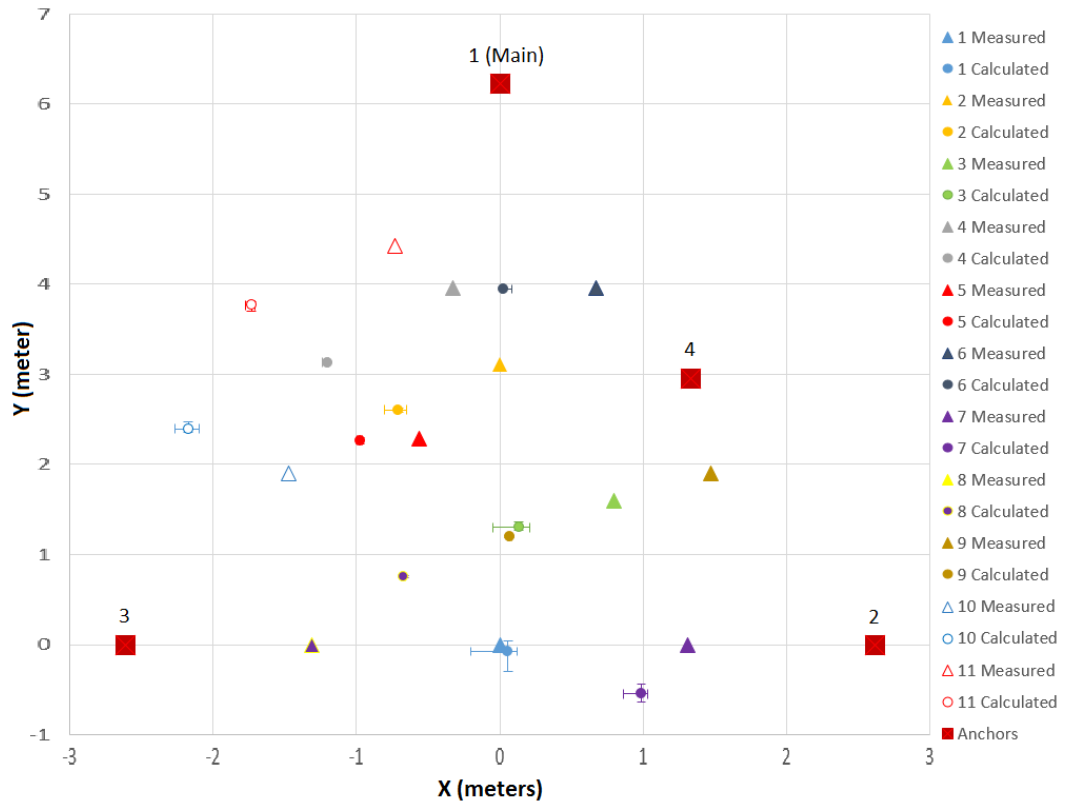


Figure 4.3: Multilateration using 4 anchors

for each position was significantly decreased for the y coordinate of the mobile node positions.

Table 4.3: Errors in the 4 anchor linearized model

	x	y	distance
Mean Error	0.68	0.45	0.81
Max Error	1.40	0.83	1.63
Min Error	0.06	0.02	0.06

4.2.3 Five Anchor Nodes

Introducing the fifth node to our system further decreased the error of calculated position. The placement of the fifth node across from the fourth node results in more comparable gains between the x and y direction of 40% and 33.3% increase in accuracy. This experiment also reduced our final mean error of distance to less than half a meter as shown in Table 4.4.

Table 4.4: Errors in the 5 anchor linearized model

	x	y	distance
Mean Error	0.4	0.30	0.49
Max Error	1.00	0.66	1.17
Min Error	0.07	0.003	0.07

Figure 4.4 shows that while the estimated node location has continued to become more accurate, the precision of the measurements has also increased. Figure 4.5 shows the comparison of the mean errors for the trilateration and the linearized models. From this we can see that the linearization resulted in better but comparable performance as we mentioned before. We can also identify the dramatic increases in accuracy with the placement of the fourth and fifth nodes. At this point it appears that the gains from additional nodes have not converged which means the accuracy could be further improved.

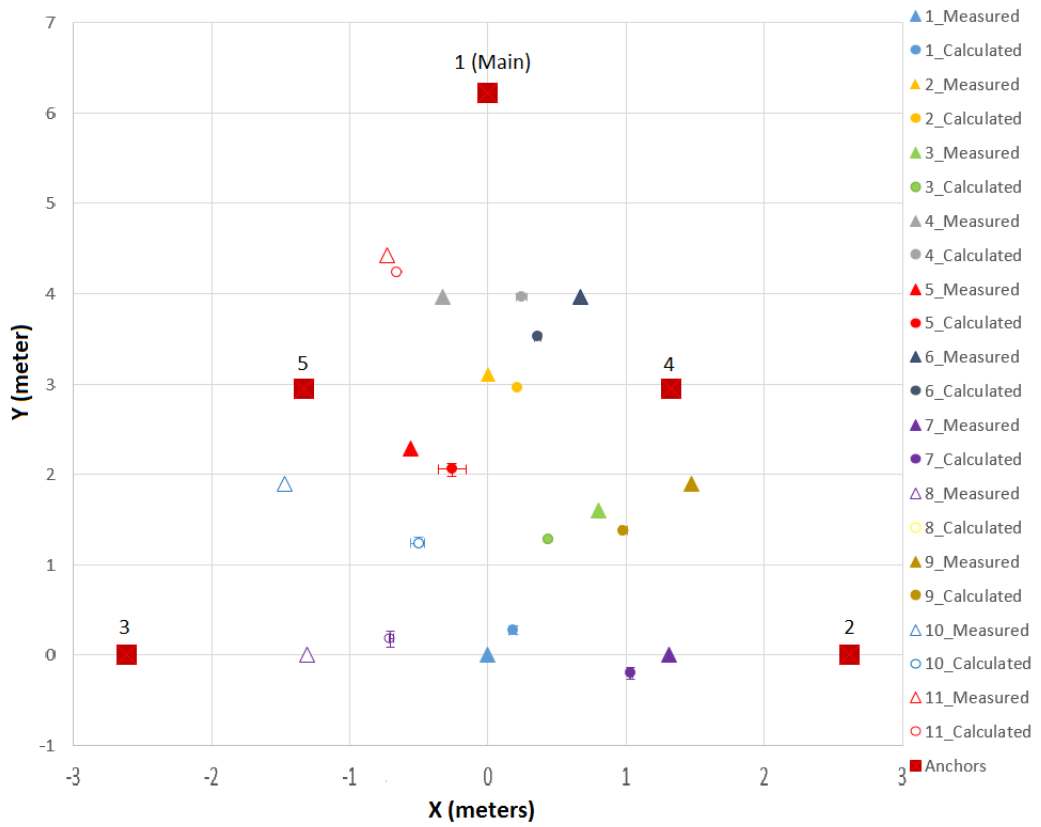


Figure 4.4: Multilateration using 5 anchors

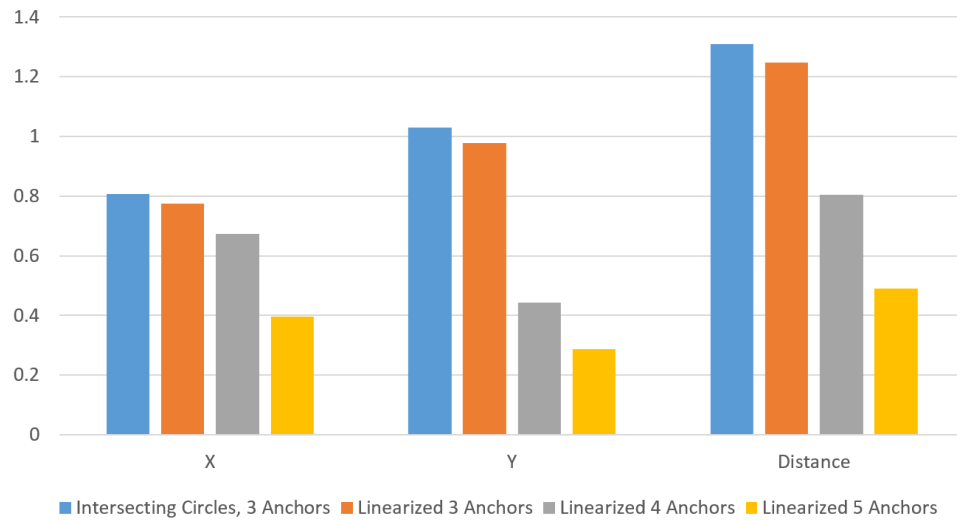


Figure 4.5: The error rate of the calculated coordinates of the mobile node relative to their actual positions. As the graph shows, the error is largest in the intersecting circles method with 3 nodes, and it decreases with increasing the number of anchor nodes in the Linearized method

Chapter 5

Conclusions and Future Work

In conclusion, we have implemented a real-time, high accuracy, low interference localization prototype that operates in the 434 MHz band and can be used for indoor (and outdoor) applications. RSSI is used to calculate the distance between nodes through FSPL. After calibrating the system, and linearizing it about a point in proximity to the target point, we are able to calculate its position with a mean accuracy of 0.49 meters using 5 anchor nodes in a 16 m^2 area. We explicitly compared our proposed system of 434 MHz RF module with a 2.4 GHz system and confirmed the extra interference on the RSSI values recorded on the 2.4 GHz system.

Experimental results from this work indicate that good signal strength estimates can be achieved. However, considerable estimation errors at certain positions remain. To increase the reliability of the 434 MHz system and reduce the incompatibility in antenna gains of different nodes in the system we provided a calibration method which improved the positioning precision. This prototype experiment is used as a proof-

of-concept implementation of the proposed technique.

For future work We will be implementing a round-robin scheme in which each node takes turn being the mobile wireless node. To ensure that each node's position can be known at all times, the mobile node is made to switch rapidly. With this round-robin scheme, each position of the node is known to all others. That is, the nodes share their addresses with each other. This will also help to develop a robust system in case one of the nodes fails and is unable to send data. Other tools for doing the estimation include particle filter, and Kalman filters. In the future, those can be investigated for this hardware/frequency platform.

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