Localization of RF Nodes Using Trilateration in a Network

Sina Kahnemouyi, Amir Pourshafiee

***Abstract*—Existing researches on wireless localization are mostly focused on 2.4GHz modules which usually experience dramatic signal interference from other 2.4GHz WiFi devices. In this paper, we propose a 434MHz RF localization using a network of at least 3 stationary wireless nodes for precise localization of mobile nodes in the network. In our implementation we have revisited and utilized networking concepts such as collision avoidance and error detection.**

RSSI (Received Signal Strength Indication) technique coupled with calibration techniques have been used to compute the position of an RF node with respect to other 3 stationary nodes and increase the accuracy of the estimated position. The built prototype is then compared with a similar 2.4GHz system and the differences are highlighted. The results reveal the feasibility and shortcomings of these systems for designing a more accurate real-time position monitoring system. In conclusion, a different approach for wireless localization is mentioned and proposed for future work.

***Index Terms*—Network, localization, trilateration, wireless, RF network localization.**

I. INTRODUCTION

LOCALIZATION has gained essential momentum in the past decade that the processors, transreceivers, and sensors are mass produced for lower prices. We are interested in robotics applications of localization to trilaterate a unit carrying a wireless RF transreceiver, the RFM22B-S2 in a field.

In places that the GPS is not functional, this method could help localize units with the RF module. We will use the following networking concepts: physical layer protocols in addition to custom higher level protocols to control the communications and collision detection/prevention.

A. Related Work

Numerous researches have been done about indoor localization techniques using RSSI (Received Signal Strength). These papers examine different wireless physical layer protocols such as Bluetooth, Wi-Fi and ZigBees. Although, most of these researches acknowledge that RSSI is not the most reliable way of localization some systems have been more successful in achieving better accuracy than others.

Bluetooth: Most of the research papers for localization done using Bluetooth received signal strength, suggest that Bluetooth, although readily available in many mobile devices, is not a very accurate way of measuring distance between two nodes. Example of research done[1].

Wi-Fi and ZigBees: RF signals at 2.4GHz frequency although they are usually more power hungry than Bluetooth provide more accurate positioning based on the received signal strength by each node. Most of the research on RF modules in this frequency range suggest that the accuracy of these systems can be as good as 1m. However, 2.4GHz Wi-Fi devices are used all around us and can interfere with the localization signals and add substantial noise to the received Signal Strength, which subsequently decreases the accuracy of the estimated position.[2,3]

Our RF localization system runs in the 434MHz frequency band, which is not used as widely as 2.4GHz, and therefore will usually experience less interference. Although, we did not expect a better accuracy than with 2.4 GHz devices under minimal interference situations, the sole fact that 434MHz waves are less likely to experience interference produces more reliable results in various environments. This system can cover a range of about 200 meters, which serves very well for applications that require the positioning of objects in larger areas.

B. Applications

Today wireless localization systems are used extensively in indoor public places such as libraries and schools to help people navigate to their indoor destination. However, our target application for designing this RF localization system is for autonomous navigation rovers, which either require a better accuracy than GPS or need to navigate in indoor locations where GPS rarely works.

One set of applications for autonomous rovers can be narrowed down to assistive rovers. Assistive rovers often times need to find their way from one room to the other. Our RF system can be easily installed in many places such as apartments and houses, or even public places such as hospitals to enable rovers to autonomously find their way.

The large range of 200 meters for each of the wireless nodes in our system can allow autonomous rovers to navigate in larger areas and therefore be used as mine finding rovers to scan a large area in places that are dangerous for people to traverse. Similar rovers can also be useful in disaster situations to locate survivals in smaller neighborhoods in a city.

December 18, 2014

II. METHODS

A. Hardware

For this project we used a 434 MHz radio module, the RFM22B-S2 with an effective range of 200 meters given that the proper antenna is used. We used wire antennas of length 17cm which according to the module specifications and

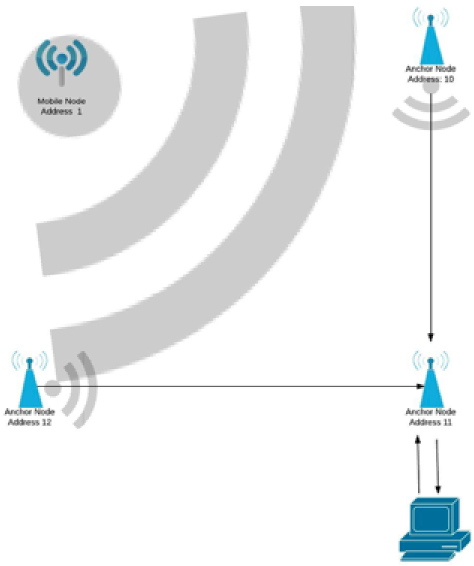

Fig. 1. This figure illustrates how the information collected by each anchor node is gathered in the main anchor and eventually transferred to the client computer to compute the position of the mobile node.

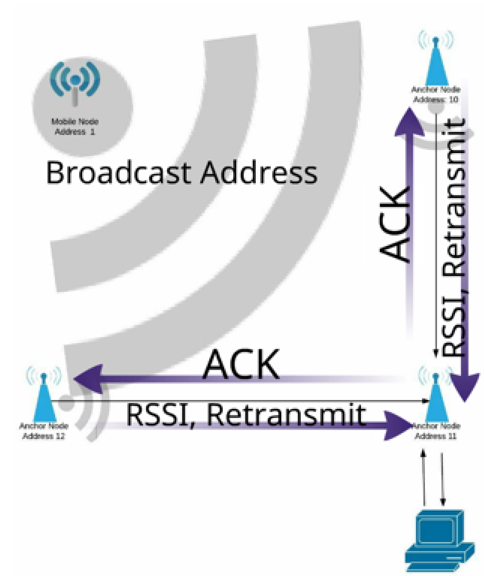

Fig. 2. Reliable communication between the main anchor and the two other anchors insures the delivery of the packets.

datasheet impedance matched the module. The communication between the modules and the microcontrollers (ChipKit Uno 32) was done by SPI. Each node unit could be powered using a USB power cables.

B. RF Node System and Relationships

Our RF localization system consists of 3 stationary nodes as wireless beacons (Anchor nodes), in addition to one or more wireless mobile nodes (Tag), 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 three 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 in a computer to compute the location of the mobile nodes and present them to the user.

We examined three different approaches on how the RSSI information from the mobile nodes should be gathered in one place to compute the position:

1) All anchor nodes send their received tag signal strength to all other anchor nodes. This way all anchor nodes can individually calculate the position of the tag node. (Distributed network)
2) All three anchor nodes send their received tag signal strength separately to a master computer which calculates the position (centralized master/slave system)
3) One of the three anchor nodes will be the master anchor node that collects the tag signal strength from other anchor nodes (Ethernet, Serial, or Wireless) and then calculates the distance. (another centralized master/slave system). The high level state diagram of the communication is illustrated in figure 1.

Although all three approaches were feasible, we concluded that the last approach suits the purpose of our application the best.

In the first approach all anchor nodes individually calculate the position. There are two problems with this approach: 1. Anchor nodes are responsible for time sensitive actions. Calculating the position of each node requires more processing time, which can risk the processing of the incoming information on time. 2. Anchor nodes (using basic microcontrollers) have limited memory and it wouldn't be optimal to store the position of all potential mobile nodes (up to 250 modes) on each microcontroller.

The second approach is based on a master and slave design. A fast computer with a large memory capacity such as a personal computer can be used to compute the position of the mobile nodes without risking the time sensitive responsibilities of the anchor nodes. However, the problem with this system was that all stationary nodes has to send their information about each mobile node directly to the computer wirelessly or using a separate cable for each. Therefore, the client computer has to either be equipped with an identical RF module, or all three anchors have to be connected to the same computer using wires which would create constraints.

The third approach illustrated in figure 1 has the best of both worlds without their limitations. In this system we set one of the stationary nodes as the main anchor and all other stationary nodes send their data to this main node. After the main server receives all the information, it does not compute the position by itself, but rather sends 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 visually.

C. 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, was implemented to prevent collisions and insure 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.

1) Transmission and Receipt Process: When an addressed message is sent, the sender will wait for an ACK, and retransmit after the timeout for the maximum number of retries. The retransmit timeout is randomly varied between a set timeout and timeout times 2 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.

In 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 acknowledgement or retransmission in case multiple messages are sent at the same time.

2) Broadcast Messages: Unlike the communication among the anchor nodes, the communication between the mobile nodes and the anchor nodes does not need does not need the confirmation of delivery. Also each mobile node needs to send transmit to all the anchor nodes at the same time. Since there are only three anchor nodes, each mobile node can transmit three messages to the address of each of the anchor nodes; however, this causes unnecessary delays between each transmission. Instead, each mobile node broadcasts its own address to a broadcast address which all anchor nodes recognize in addition to their own distinct addresses. This way, only one transmitted message is received by all anchors with very small receipt time differences.

However, broadcasts are not acknowledged or retransmitted and are therefore not actually reliable. The reason for not acknowledging the broadcasted messages is that we want our system to be capable of handling a lot of mobile nodes and if each broadcast message by mobile node has to be acknowledge the chance of network congestion and collisions increases drastically.

3) Frames and Headers: RFM22B hardware module supports the transmission and receipt 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 driver 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 and acknowledgement frame and indicates that the frame does not include data to follow.

D. Addressing

A two byte addressing system is used for all nodes in the system. This provides a maximum of 256 addressed nodes (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 illustrates how the 2 byte address space is divided for the described purposes:

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

Fig. 3. 2byte addressing scheme for each node

E. Calculations and Trilateration

To calculate the coordinates of the mobile nodes, we needed to calculate the distance that each mobile node makes with the anchors. We chose to calculate this distance the drop in the signal strength. We first calculated the distances and then performed a trilateration algorithm to calculate the nodes' coordinates.

1) Free Space Path Loss (FSPL): To obtain the distance that the mobile wireless node made with each of the anchors, we used the Free Space Path Loss (FSPL) principle. The FSPL phenomenon works on the basis of signal attenuation in a medium (dry air for our uses). It is important that the RF modules have lines of sight with eachother to avoid RF reflections and diffractions[4]. FSPL can be calculated as follows[5]:

$$FSPL(dB) = 10\log\left(\frac{4\pi df}{c}\right)^2 \tag{1}$$

where c is the speed of light, f is frequency and d is the distance. By rearranging equation 1, we have:

$$FSPL(dB) = 20log(d) + 20log(f) + 20log\left(\frac{4\pi}{c}\right) \tag{2}$$

where $20log\left(\frac{4\pi}{c}\right)$ is calculated to be -27.55 when distance is in meters and frequency is in MHz. $20log(f)$, for the 434 MHz modules that we used is 52.75. By placing these values in 2, we have:

$$FSPL(dB) = 20log(d) + 25.2$$

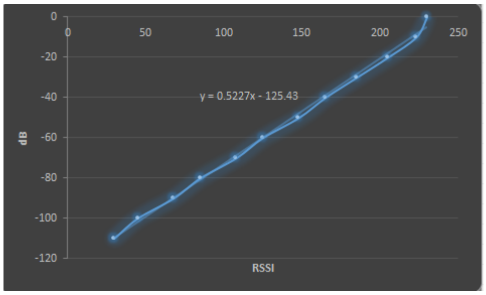

Fig. 4. RSSI vs dB graph and linear regression formula

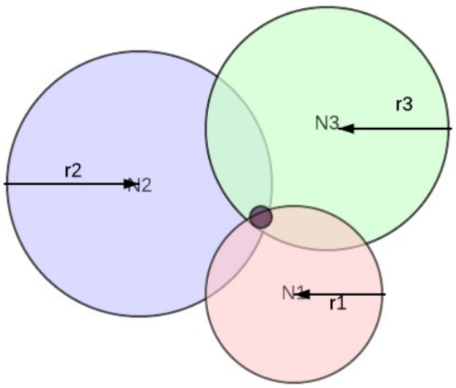

Fig. 5. Coinciding circles that represent the radio signal strength of the nodes in 2 dimensions

If we solve it for distance d, we get:

$$d = 10^{\frac{|FSPL| - 25.2}{20}} \tag{3}$$

To calculate the dB value of the signal, first converted the RSSI value to a signed number and then ran the linear line regression algorithm to obtain the conversion formula to calculate the signal strength as illustrated in figure 4:

$$SignalStrength(dB) = 0.5227RSSI - 125.43 \tag{4}$$

Since the value of RSSI is 0dB when the modules are close to each other, the value of FSPL is the same as the absolute value of the number obtained by equation 4.

2) Trilateration Calculation: To calculate the trilateration formula, we were given the distances that the mobile node makes with each anchor node. The mobile node receives signal strengths from each node that can is converted to a distance and thus can be thought of as the radius of the sphere. For simplicity, we only experimented in 2 dimensions and thus we did the calculations for two dimensions as well. Assuming that we know the position of each node, we can calculate the position of the mobile node which is the intersection of the radii from anchor nodes as can be illustrated in figure 5.

$$r_1 = r_2 = r_3 \tag{5}$$

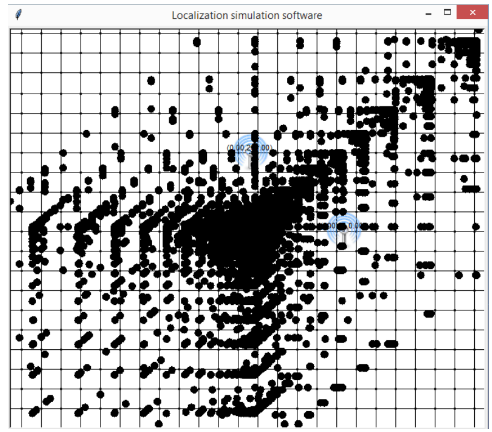

Fig. 6. Simulation of trilateration of 1000 random RSSI data sets

To calculate the x component of the mobile node's coordinate, we divide equation 6 by equation 7[6].

$$f = \big((r_1^2 - r_2^2) + (x_2^2 - x_1^2) + (y_2^2 - y_1^2)\big)(2y_3 - 2y_2) - \big((r_2^2 - r_3^2) + (x_3^2 - x_2^2) + (y_3^2 - y_2^2)\big)(2y_2 - 2y_1)) \tag{6}$$

$$g = ((2x_2 - 2x_3)(2y_2 - 2y_1) - (2x_1 - 2x_2)(2y_3 - 2y_2)) \tag{7}$$

$$x = \frac{f}{g} \tag{8}$$

and the y component can be calculated by:

$$y = \frac{((r_1^2 - r_2^2) + (x_2^2 - x_1^2) + (y_2^2 - y_1^2) + x(2x_1 - 2x_2))}{(2y_2 - 2y_1)} \tag{9}$$

F. Simulations

By generating 1000 random values between 0 to 80 dB, we simulated the experiment using the trilateration equation. We rounded the decibel value to the closest decimal level (since our modules had a 0.5 decibel precision). The result of our simulation is depicted in figure 6. The discreetness that appears in the graph is due to the roundoff error. The larger the dB value, the larger the error becomes since it is affecting the exponent. (Recalling equation 3)

III. Challenges and Results

Based on the previous research done on this topic, we expected some unreliability in localization systems based on RSSI values. As we tested our systems we noticed that if the antenna gains changed slightly from one node to another it could result to discrepancies among the RSSI values which subsequently increased the error in the computed position of each node dramatically. Therefore, we added a calibration step to the beginning of our localization process.

In the calibration process the client positions the mobile node 2 meters away from each stationary node at a time while the system calibrates itself based on the RSSI values that it receives in real-time. This process helps the system to produce more relevant positions based on the most recent antenna gain conditions.

As a reference we compared our tests to a system that we built with the same configurations but with a 2.4GHz Xbee RF modules. The test configurations in both cases consisted of 3 anchor nodes in a right triangle form where the distances of each of the anchor nodes from the main anchor were 2 meters. During the day on campus, when more people were using their Wi-Fi devices we noticed that 434MHz RF system produced much more reliable results than the Xbee devices. The 434MHz devices produced a consistent error of about 1 meter; on the other hand, the XBee devices experienced consistent interference and produced inconsistent RSSI values. However; in outdoors and late night indoors Wi-Fi interference was substantially reduced and Xbee devices produced a similar error rate of about 1 meter. However, even in these conditions the small interference that was still present resulted in a better accuracy for the 434MHz devices.

IV. Conclusions

In this paper, a real-time indoor and outdoor tracking application prototype is presented. RSSI technique is employed to estimate user's location in a hybrid of indoor and outdoor environments. We explicitly compared our proposed system of 434MHz RF module with a 2.4GHz system and confirmed the extra interference on the RSSI values recorded on the 2.4GHz system.

Experimental results from this paper indicate that good signal strength estimates can be achieved. However, considerable estimation errors at certain positions remain. To increase the reliability of the 434MHz 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.

Although 2.4 GHz experienced a lot more interference and noise, small amount of interference was also present for the 434MHz system. Even though, we recorded smaller errors using the 434MHz system, applications that require a better accuracy than 1 meter need to use different localization techniques such as TDoA (Time Difference of Arrival).

Systems like DecaWave's RTLS chip that can be as accurate as 10cm for the distance between two nodes. This particular kind of RTLS chip works in 3.4-6 GHz spectrum and uses TDoA(Time Difference of Arrival) instead of RSSI. In TDoA systems rather than computing the distance of other nodes based on the strength of the arriving signal, the distance is measured based on the roundtrip time of an RF signal. http://www.decawave.com/

The next step for us is to implement a TDoA localization system and record the measured distances in both systems and find out why TDoA is a more reliable and accurate system of wireless localization.

Appendix A
Python code for calculations and Graphic User Interface

Appendix B
Division of Tasks

Sina Kahnemouyi was in charge of the firmware desing, wireless network design, and Network Amir Pourshafiee was in charge of creating and decoding datagrams, hardware desing, trilateration, and User Interface.

Acknowledgment

This research paper is made possible through the support and feedback of our instructor and TA from the CMPE252A class at UCSC.

We would like to specially thank Dr. Katia Obraczka for her support and encouragement. She kindly and promptly responded to all of our questions and concerns. In addition, her lectures were extremely helpful for transforming this project from an idea to a well thought and organized wireless network system.

References

[1] A.Barreria, P.Sommer, et.al.*Collaborative Localization of Mobile Users with Bluetooth: Caching and Synchronisation*
[2] E.Lau and W.Chung *Enhanced RSSI-based Real-time User Location Tracking System for Indoor and Outdoor Environments* International Conference on Convergence Information Technology. 2007.
[3] R.Mardeni and O. Shaifull Nazim *Node Positioning in ZigBee Network Using Trilateration Method Based on the Received Signal Strength Indicator (RSSI)*European Journal of Scientific Research. Vol.46 No.1. 2010. pp48-61.
[4] *IEEE Standard Definitions of Terms for Antennas*. IEEE. 1983.
[5] I.Poole *Free Space Path Loss: Details, Formula, Calculator* Radio-Electronics. Resources and analysis for electronics engineers.
[6] Farrah and L.Cottrell *TULIP Algorithm Alternative Trilateration Method* Confluence. SLAC. Stanford University. 2012.
[7] *RadioHead Packet Radio library for embedded microprocessors*