European Journal of
Engineering & Environmental Sciences

RESEARCH ARTICLE

Investigation of Received Signal Strength (RSS) as a Matrix for Localization in Wireless Sensor Networks (WSNS)

Abonyi, Dorathy O.

Department of Electrical and Electronic Engineering, Enugu State University of Science and Technology, Enugu State Nigeria

***Corresponding Authors:** Abonyi, Dorathy O., Department of Electrical and Electronic Engineering, Enugu State University of Science and Technology, Enugu, Nigeria.*

ABSTRACT

Insecurity of human and properties in Nigeria has risen to an alarming situation and calls for immediate attention. Kidnapping has become so rampant that these days not only the wealthy adults are kidnapped but also vulnerable children and the elderly. Technology like the mobile phone which was expected to be a source of development and ease of life has become a supporting tool that these hoodlums use to perpetuate their actions and put the nation in tears all the time. This research investigates the use of Received signal strength (RSS) which is readily available in all mobile devices as a matrix for locating these hoodlums and consequently, the abducted. In this investigation, a model of a wireless network scenario was developed and simulated in MATLAB. The investigation first assumed that radiating element at the base station (localization system) was equipped with a single dipole element and then secondly, a collinear antenna. The user devices were programmed ESP8266 WIFI modules equipped with onboard antenna. RSS data were collected at the base station and analyzed to ascertain if RSS is a practical matrix for Localization system implementation. Both simulation and experimental results has shown the following; that measured RSS decreases with increase in distance and so can be used to develop a range estimation model, influence of the environment is a major impairment to accurate RSS measurement but if the environment is known, the error due to environment can be compensated for in the localization algorithm, more accurate result in RSS-based localization system is possible if decision is based on multiple scans than on a single scan.

***Keywords**: Localization, Wireless Sensor Network (WSN), Received Signal Strength (RSS), Matrix*

Introduction

The technology of localization in wireless networks has become very popular due to its wide range of applications which include navigation, environment sensing, home automation, human and animal tracking/health condition monitoring, Internet of Things (IoT), and most recently as a strategy for small cell deployment as proposed in (D. Abonyi, 2019). In Wireless Sensor Networks, localization can be defined as the process of estimating the spatial coordinates of users scattered at unknown positions in space from at least one anchor node or a base station of a known location. The technology of localization in WSNs can be broadly classified as range-free and range-based localization. Range free is a proximity-based localization method that determines the location of nodes using hop-counts or connectivity between nodes. The hop-count values between anchors and unknown nodes are transformed into distance information based on the computed average size of a hop (hop-distance). The complexity of range free method increases as the network coverage area increase so it is not ideal for large networks like a cellular network. The range-based localization approach involves the knowledge of the location of a base station node, a coordinator node, or an anchor node from where the location of the target nodes is estimated. The signal received from the target node during this communication can be characterized by the time of arrival (TOA) (Mekonnen &

***Citation:** Abonyi, Dorathy O. (2022). Investigation of Received Signal Strength (RSS) as a Matrix for Localization in Wireless Sensor Networks (WSNS). European Journal of Engineering and Environmental Sciences, 6(1), 29-38.*

***Accepted:** February 18th, 2022; Published: February 28th, 2022*

Wittneben, 2014) or time-difference-of arrival, (TDOA) (Wookjin et al., 2008) or its reduction in power as it propagates over distance (attenuation) in the form of received signal strength (RSS) (Vallet Garcia, 2015). This information can then be used to calculate the angle of arrival (AOA) or the position (Patwari et al., 2005). The time-dependent localization method requires accurate clock synchronization which makes the system complex and difficult to implement. Received Time of Flight (RTOF) is another time-dependent approach that tries to solve the problem with beacon node synchronization. In this approach, the time and distance of signal received is not measured, rather the beacons send back the signal or an acknowledgement signal to the sender who now calculates the round-trip time of the signal and uses it to calculate how far away it is from the beacon meaning self-localization. In real life application, the latency in response maybe unpredictable and uncontrollable since it is subject to many factors such as how busy the receiver was when the message arrived and so the accuracy of RToF approach is not assured. On the other hand, because environment characteristics is not considered in time dependent approach, it is highly affected by multipath causing inaccuracy in range estimation.

RSS-based localization involves using measured signal power received from a distant transmitter to estimate radio device location. Two popular approaches to RSS-based localization are by fingerprinting or by using statistical prediction. The former involves online and offline phases. During the online phase, a set of measured RSS from different locations within the coverage area is acquired and stored in the database as a radio map of that area. During the online phase, measured RSS is matched to the existing RSS-distance values in the database and the closest match forms the location of the sensor node. This approach involves extensive measurement and needs to be updated as the environment changes due to new construction etc. The statistical prediction approach uses path loss models that relate the losses in the environment to the RSS expected at different distances between transmitter and receiver to develop a mathematical model that is used for future distance prediction based on measured RSS. This is mostly applied in a centralized localization requiring only a single anchor node which determines the location of every other node in that network. Alternative approaches are triangulation (Thrivikrama et al., 2011), trilateration, or multilateration (Attanayake & Yue, 2012). These approaches involve the use of multiple anchor nodes of known positions each of which estimates the distance or angle or both from a sensor/user node. The intersection of these distances or angles forms the location of the sensor/user node. RSS-based localization technique is simple and cheap requiring no extra hardware on the mobile device or synchronization thereby making it popular in wireless sensor networks. RSS-based localization technique has the advantage of availability in all radio devices, anonymous data is used and so user privacy is assured and existing wireless infrastructure is being reused requiring no additional hardware on the mobile devices. RSS-based localization has been shown to have poor accuracy especially in indoor. Researchers therefore question the applicability of RSS for the purpose of radio device localization in wireless network (Heurtefeux & Valois, 2012).

To improve localization performance, papers like (Coluccia & Fascista, 2018) explored a hybrid approach of both TOA and RSS. Though better accuracy was achieved, a more complex and more expensive system is involved. This paper experimentally investigates to confirm if RSS alone can be used to achieve a meaningful localization in wireless networks or not.

2. Methodology

The investigation of RSS as a Metrix for localization was based on simulation as well as experimental work. First, a wireless network model based on the free-space propagation model was created in MATLAB. A single dipole, as well as a collinear antenna, was used in the based station model to investigate the RSS relationship with distance. The base station was located at a reference point within the network coverage area to investigate the applicability of RSS for localization system implementation. Mobile users to be located were modeled as randomly scattered points within the network coverage area equipped with radio frequency radiating elements. RSS-distance classification was simulated to find out if there is an exponential decrease in RSS with distance as expected in theory. Experimental verification of the simulation was carried out using WiFi nodes operating at an unlicensed frequency spectrum of 2.45GHz. A 5-element collinear antenna was used in the base station for further investigation. Simulated as well as experimental results were obtained and critically analyzed in each section.

Simulation

Propagation Channel Model

The simulation was carried out in three stages in MATLAB, first, the network environment was simulated for a 200 m^2 environment to mimic the experimental testbed. Secondly, the RSS model was developed to calculate the received signal strength from user devices within the coverage area and lastly, a noise model was developed to investigate the effect of noise on RSS. It was assumed that the base station is located at (0.0) coordinate (center of the space) of the simulation environment such that the network coverage area goes from -100 to +100 vertically and horizontally. The base station comprises a simple dipole element with a gain of 2.14dB and radiating omnidirectionally within the coverage area. A simulation model of the environment is shown in Figure 1.

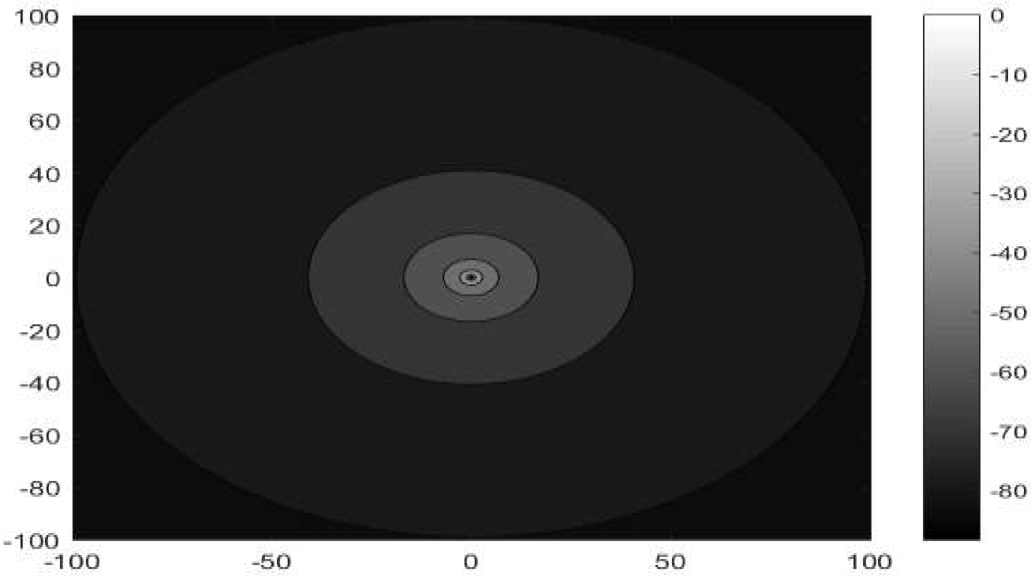

Figure 1: A Simulation Model of the Network Environment in MATLAB as a Testbed RSS Investigation

A model of the wireless connectivity between the base station and the users in the network was carried out by applying a link budget equation. A link budget calculates the signal level through the link and predicts the received signal strength (RSS) at the other end of the communication channel as illustrated in Figure 2. There are three stages in the link budget schematic shown. The transmitting end (Base station (BS), Tx antenna cable, and Tx antenna) transmits power (P_{TX}) with an assumption that both cable and connector losses are negligible (L_{TX} = 0).

Figure 2: Illustration of wireless Communication Channel for Link Budget Calculation

The channel is the air interface characterized by path loss and other influential factors like humidity and terrain roughness. For the link budget modeling in this simulation, the only environmental factor to be considered is the path loss with the assumption that other factors contribute a negligible loss to the environment. The receiving end (AP, RX antenna cable, and RX antenna) has some losses due to the connector and cables which were not neglected. It also has a sensitivity that defines the minimum useful RSS that the receiver can handle. The length of a communication link has a major influence on the link budget. The link budget equation is given by: $P_{Rx} = P_{Tx} + G_{Tx}(dB) + G_{Rx}(dB) - (L_{Tx} + L_{Rx} + PL)$ 1

Where $L_{Rx} = C1_{Rx} + C2_{Rx}$ and $L_{Tx} = 0$, $C1$ and $C2$ are cable and connector losses respectively in dB, P_{Rx} is the received power (RSS) and P_{Tx} is the transmitted power both in dBm. G_{Tx} and G_{Rx} are the transmitting and receiving antenna gains in dBi respectively. R_{in} is the receiver sensitivity in dBm and PL is the channel path loss. Assuming a free space environment, the link budget equation above then becomes:

$$P_{Rx} = P_{Tx} + G_{Tx}(dB) + G_{Rx}(dB) - (L_{Tx} + L_{Rx} + FSPL) \text{ .... } 2$$

$$FSPL = -27.5 + 20\log(f) + 20\log(d) \text{ .... } 3$$

where f is radio wave carrier frequency in MHz, d is the distance between transmitter and receiver in meters. $FSPL$ stands for free space pathloss.

Received Signal Strength (RSS) Model

The link budget model equations were then applied to calculate what the received signal strength will be at the base station position from all possible user positions. In this part of the simulation, the effect of antenna gain on measured RSS was investigated by modeling a dipole as well as a collinear antenna radiating in free space as the base station antenna. Using Equations 2 and 3, RSS from users were calculated at the base station position. Since choice is flexible for base station antenna, RSS model using 5 dipole element collinear antenna with a gain of 9.13dBi was also implemented at the base station (localization system), where the gain of a collinear antenna is given by $G_c(dBi) = 10\log(n) + G_e(dBi)$, n is the number of elements and Ge is the element gain in dBi. For this investigation, a wider coverage area of 2.5 km range was applied and results of up to 1.5 km coverage were shown in Figure 3.

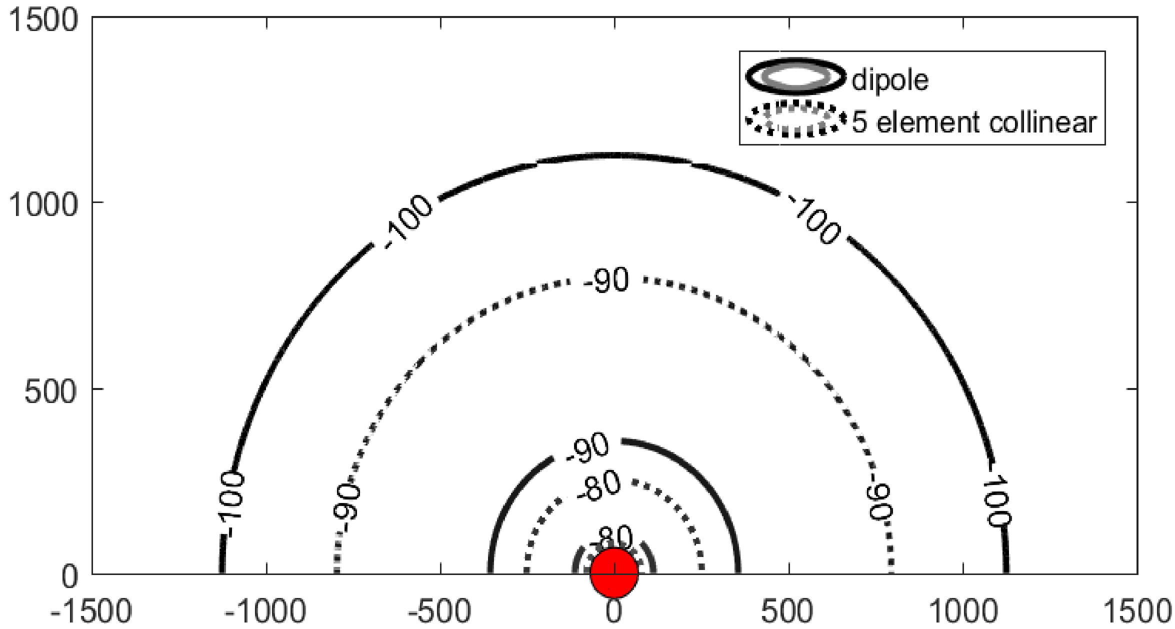

Figure 3: Effect of Antenna Gain on Measured RSS

This result has shown that with a dipole at the transmitter and receiver, an RSS value of −100 dBm is obtained at 1.1km, and upgrading the receiver antenna to a collinear antenna would measure the RSS value of −98dB at a distance of 2km. This is an indication that with a high gain antenna, better RSS will be received from a longer distance, more coverage area can be achieved and there is a higher possibility of achieving a relatively accurate RSS-based localization system. This is to say that a high gain antenna is required at one or both ends of the communication link for a practical RSS-based localization system.

Noise Model

Practically, all environments are characterized by noise, attenuation, and interference. It is also prone to change in characteristics due to changes in vegetation or construction of new buildings etc. The effect of these environmental changes on radio wave propagation was investigated. Normally noise in information theory is modeled as additive white Gaussian noise (AWGN) which is a basic noise model used to mimic the effect of many random processes that occur in nature. Any noise experienced in the environment would cause an error in measured RSS for an RSS-based localization system. An investigation on how much of range estimation error will be encountered for a deterministic error of ±1σ in simulated RSS in an FSPL environment was carried out. Figure 4 shows the result of this simulation.

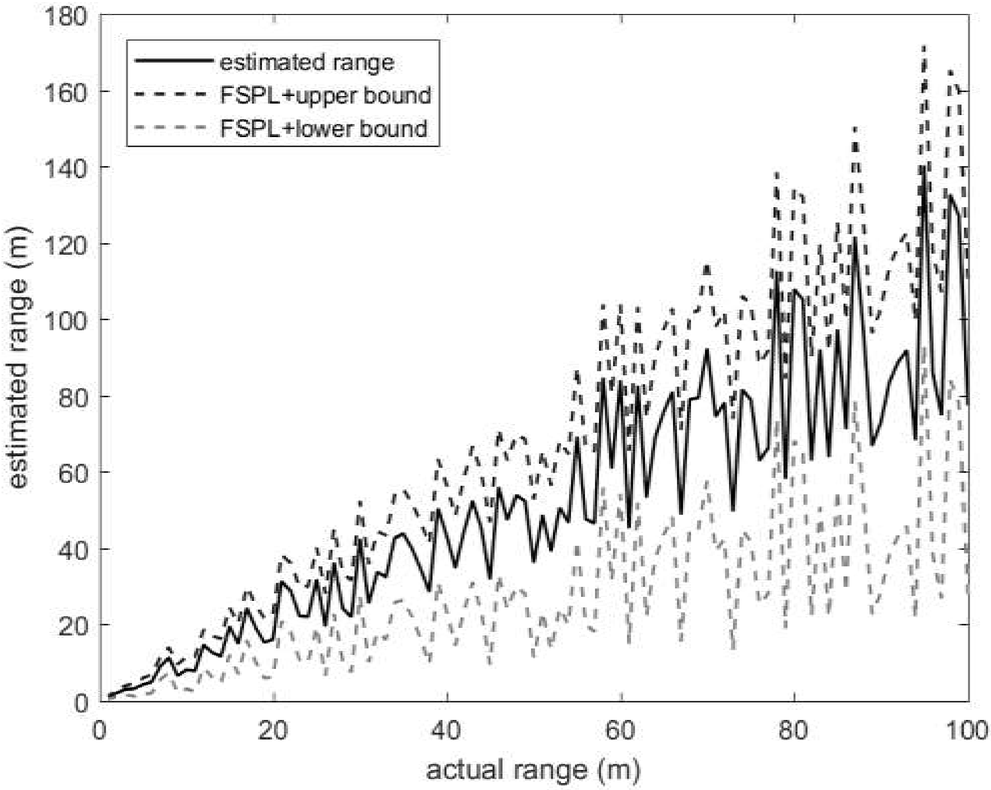

Figure 4: Effect of Noise on Measured RSS

It was observed that in RSS-based location estimation, noise during transmission will either cause over-estimation or under-estimation of user location. If the environment is known, these possible noise sources can be characterized, developed into a mathematical model that can be used to compensate for the effect of the noise on RSS (D. O. Abonyi, 2018). It can also be observed that the effect of noise on the signal increases with an increase in distance. This means that if the effect of noise is not mitigated in the system, at a certain distance away from the localization system, the estimated user location may completely be different from the actual location.

Experimental Investigation

Outdoor Round-Trip RSS Measurement

The first investigatory test was the round-trip measurement. This is to confirm the existing theory which states that RSS decreases exponentially with distance. This is necessary because, for a range-based localization, estimation is based on this theory. To check if this is true, a 9dB Omni-directional antenna from RF Technics Limited was connected to the ESP8266 thing through the external antenna UF.L connector provided on the board. The ESP8266 was programmed to scan the WiFi network and measure RSS. One user already programmed as AP with user ID 'DorathyWiFiNode40' mounted on a tripod stand was held to walk 1m from the observer point position in an open field at ESUT, Agbani to about 100m distance away from the system and then back to the system. The measured RSS (dBm), as well as a fitting curve showing the calculated RSS, is shown in Figure 4.

This result shows that as the user moved away from the base station, measured RSS decreased but increased as the user walked back toward the base station position. This has confirmed the existing theory that there is an exponential relationship between RSS and distance. The measured data have shown scattered points with variations when compared with the expected data. This is due to multipath and variation in height as 'user' is being moved to and fro.

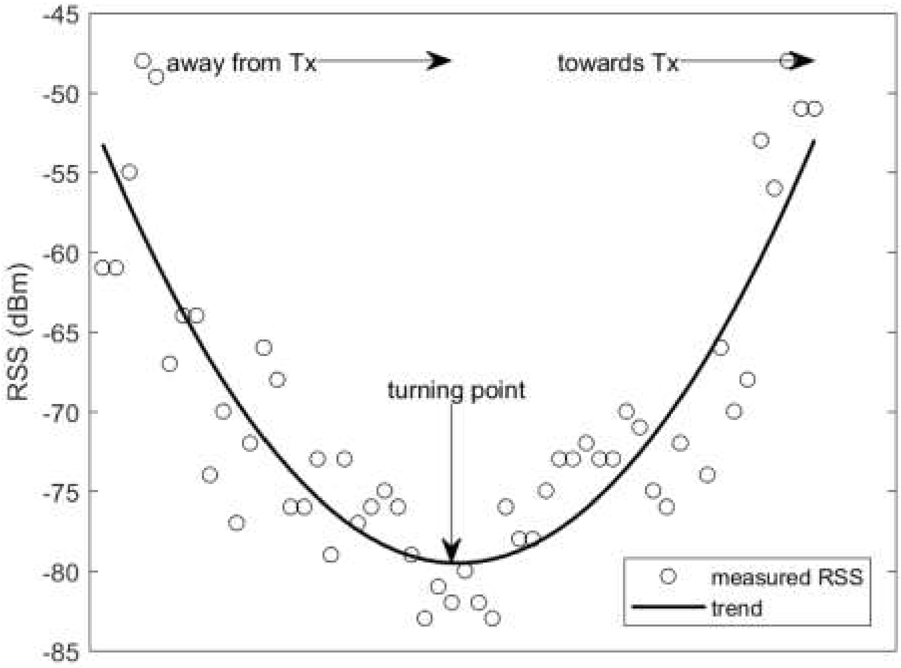

Figure 5: Round-trip RSS Measurement

Outdoor RSS-Distance Relationship Test

This second test is aimed at testing the relationship between RSS and distance using multiple scans. This is to certify that there is a close relationship between measured RSS at each distance. The experiment to obtain data for this test was performed using a single 9 dB Omni-directional antenna connected to the ESP8266 thing. The ESP8266 was programmed to perform ten WiFi scans at every scan period. User ‘DorathyWiFiNode40’ was used as the network user in this experiment. Measurement was performed at every 1m distance from the observer point up to 100m distance. At each distance, ten RSS measured data from each scan were obtained and plotted in Figure 5.

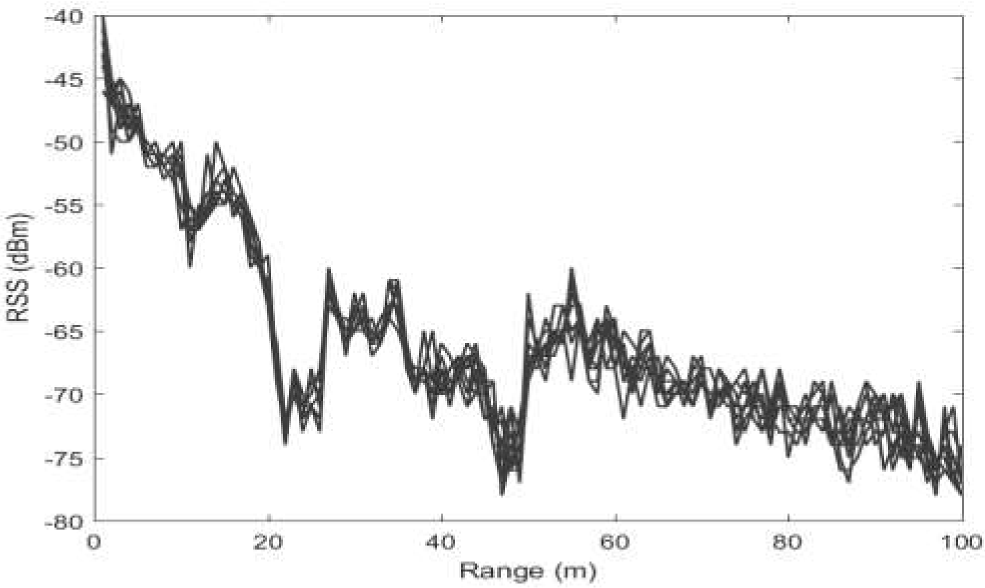

Figure 5: Multiple Scan Approach to RSS-Based Localization

Obtained data were used for statistical analysis to test the RSS-distance hypothesis. From this result, it can be observed that deep nulls are obtained at distances 11m, 22m, and 47m from BS. This draws attention to the two-ray reflection model given by Equation 4 with the first null position given by Equation 5.

$P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2} \times 4sin^2(\frac{2\pi h_t h_r}{\lambda R})$ ………………………. 4

$R = \frac{2h_t h_r}{R}$ ………………………. 5

where P_t and P_r are transmitter and receiver power, G_t and G_r are transmitter and receiver gain, h_t and h_r are transmitting and receiving antenna heights respectively, R is a range, λ is the wavelength of radio wave, and range, where the null appears, is given by Equation (5). With $h_t = h_r = 0.9$m and for a frequency of 2.45GHz as implemented in this experiment, the location of the first signal null is calculated to be approximately $13m$ which is close to the experimental first null position of $11m$. The experimental result may have been influenced by factors like transmitting and receiving antennas being on the same height or not being high enough which are not ideal for a 2-ray model. Other nulls after the first one increase in distance by the same amount so that analytically, the second and third nulls should appear at a distance of 26m and 39m respectively. The experimental result has also shown the increase in subsequent null distances by the first null distance value. This means that the environment of measurement most likely exhibits a two-ray reflection model to be investigated further in future work. If the environment of deployment of an RSS-based localization system is known, environmental effects on the measured RSS can be predicted and be compensated to ensure more accurate results.

Outdoor Measured RSS Distribution

In statistics, Pearson's or Spearman's approaches are methods that can be used in working out the correlation between two variables. The Pearson correlation coefficient is the most widely used. It measures the strength of the linear relationship between normally distributed variables. When the variables are not normally distributed or the relationship between the variables is not linear, the Spearman rank correlation method is used. A normal distribution is expected because for multiple measured RSS at each distance, the majority of the measured values should lie close to the mean value. To check if the measured data is normally distributed, a histogram of all measured RSS is plotted as shown in Figure 6. This result has shown a normally distributed data set that is positively skewed. This means that environment of measurement can be studied and represented by a mathematical model to be used for future prediction in that environment or a closely related environment.

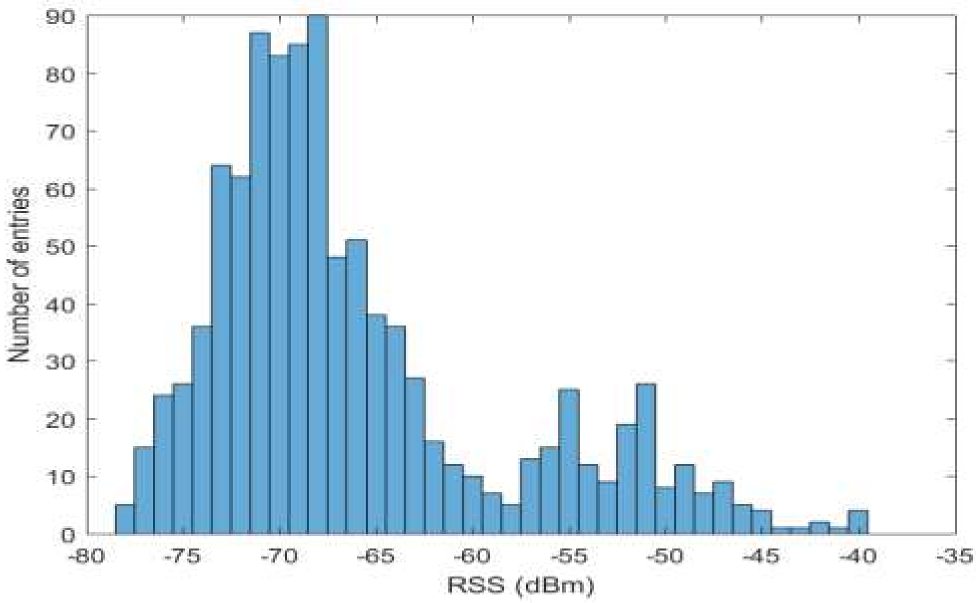

Figure 6: Histogram Plot of Average Measured RSS to Check the Distribution of Measured RSS Data

European Journal of Engineering and Environmental Sciences | EJEES
Vol. 6. No. 1 | February, 2022 | pp. 29-38
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Effect of Noise on Measured RSS

Noise in this scenario can be defined as the standard deviation of measured RSS at the same distance in the same environment. Even with the same device, different RSS is measured at the same distance due to ambient noise. To investigate what the effect of noise would be, measured RSS data at each distance for ten different network scans were plotted as an error bar of sample standard deviations from the mean. Figure 7 shows the result for each 1m interval of range. This result has confirmed that even with the same device at the same distance in the same environment, different scans will result in varying RSS values due to ambient noise. The result has shown that the standard deviation due to noise expected in this particular environment is within ±1.3dB. This standard deviation was obtained for the same radio device but can vary with different devices. Noise obtained from different environments will also be different due to the characteristics of the propagation in that environment. Signal attenuation also varies with time, geographical position, and radiofrequency in the form of fading which can be due to multipath, weather like rain, and obstacles having a shadowing effect on the propagating signal.

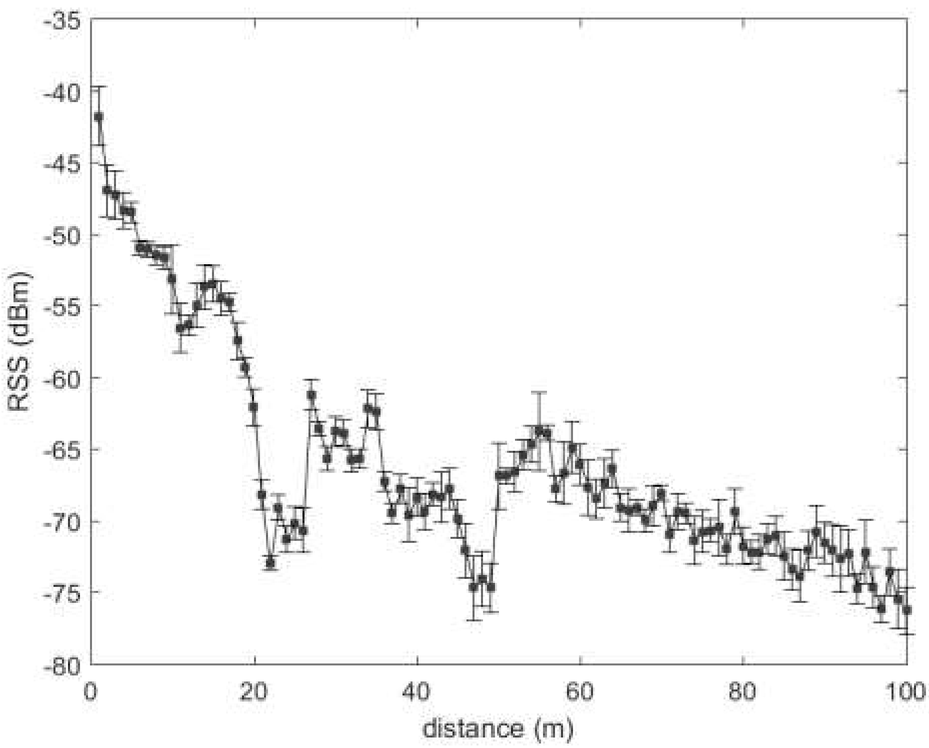

Figure 7: Effect of Noise on Measured RSS

Difference In Measured RSS Per Distance Test

A strong certainty that there is an inverse relationship between RSS and distance has been obtained. This means that as distance increases RSS decreases. There is also a need to ascertain that there is a significant difference between RSS measured at different distances, this will give assurance that RSS will have a strong relationship to distance. We, therefore, came up with a hypothesis that states that if there is a significant difference between RSS at different distances, then different RSS values can be related to unique distance values for RSS-based localization implementation. The null and alternate hypotheses are thus stated;

- H0: There is statistically no significant difference between measured RSS at each distance for all scans

- HA: There is a statistically significant difference between measured RSS at each distance for all scans

From this hypothesis, we believe that there is a significant difference between RSS values at each distance for all scan periods. A statistical correlation and P-value test were performed to find the correlation of all data from all scans with distance. The result obtained is $P_v = 3.71 \times 10^{-23}$ and $Corr = -0.793$ which rejects the null hypothesis and accepts that there is a significant difference in measured RSS between distances.

Measured RSS At Same Distance but Different Scans

It is expected that multiple scans at the same distance should have closely related RSS values. We can then state a hypothesis that If the same or closely related values of RSS are measured at the same distance at different scan periods, there will be stability in measured data, and error in range estimation will be reduced. The null and alternate hypotheses are thus stated;

• H0: There is a statistically significant difference between the scan period

• HA: There is statistically no significant difference between each scan periods

A correlation test was carried out on all data obtained from all ten scans for all distances. The correlation coefficients showing how each data set for each scan relates to another data set for other scans are shown in Table 5.1.

Table 1: Correlation between Different Scans for the Same Distance Range

Scans	1	2	3	4	5	6	7	8	9	10
1	1.00	0.97	0.97	0.97	0.97	0.96	0.97	0.96	0.95	0.94
2	0.97	1.00	0.95	0.97	0.96	0.96	0.96	0.95	0.95	0.94
3	0.97	0.95	1.00	0.97	0.97	0.96	0.97	0.97	0.96	0.95
4	0.97	0.97	0.97	1.00	0.97	0.97	0.97	0.97	0.97	0.96
5	0.97	0.96	0.97	0.97	1.00	0.97	0.98	0.98	0.98	0.97
6	0.96	0.96	0.96	0.97	0.97	1.00	0.98	0.98	0.98	0.98
7	0.97	0.96	0.97	0.97	0.98	0.98	1.00	0.98	0.99	0.98
8	0.96	0.95	0.97	0.97	0.98	0.98	0.98	1.00	0.99	0.99
9	0.95	0.95	0.96	0.97	0.98	0.98	0.99	0.99	1.00	1.00
10	0.94	0.94	0.95	0.96	0.97	0.98	0.98	0.99	1.00	1.00

From Table 1, it can be seen that all but two scan data sets passed the 0.95 (95%) scientific level required of a normal distribution. Only scan 1 - 10 and also scan 2 - 10 has values of 0.94 which is 0.01 below the required threshold. Since up to 96% of the data have shown that data obtained at multiple scans are positively correlated, there is high certainty that the data collected during multiple scans will be stable for accurate localization.

Conclusion

This paper has investigated RSS as a matrix that can be used for a radio frequency location estimation system. A wireless network environment was simulated in MATLAB as the testbed for the investigation. The RSS-distance relationship was investigated to confirm the possibility of developing a practical prediction model based on their relationship for future location prediction. It was observed that an exponential relationship exists between the two parameters in a known environment. It was also observed that environment is a big challenge to accurate RSS-based location estimation especially if the environment is unknown. Simulation and experimental results have shown that a practical RSS-based location estimation system can be achieved if the environment is carefully classified and error compensated. The environment of location of kidnapers may not be known but mathematical models can be developed for environmental approximations. This investigation, therefore, concludes that RSS-based localization systems should be employed where a precise location estimation is not a priority but an area location is required. This means that it is suitable for the purpose of this research because only an area location of kidnappers is required for security to track them down.

Acknowledgment

I wish to thank Tertiary Education Trust Fund (TETFund) for sponsoring this research in full and Enugu State University of Science and Technology for considering this research worthy of TETFund sponsorship.

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