Distance Estimation Based on RSSI and Log-Normal Shadowing Models for ZigBee Wireless Sensor Network

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ABSTRACT

In the last few years, a mobile wireless sensor and its application in wireless sensor network (WSN) are commonly used. Localization of a mobile sensor node is considered a critical issue in some WSN applications. In this paper, an outdoor environments experiment was carried out to measure the distance between the mobile node and the coordinator node in a simple point-to-point ZigBee WSN. The distance was determined based on the measured Received Signal Strength Indicator (RSSI) of the mobile node by the coordinator node. In addition, a Log-Normal Shadowing Model (LNSM) was derived for outdoor condition. Moreover, the parameters of the propagation channel such as standard deviation and a path loss exponent were estimated. The RSSI was measured and analysed for outdoor environments for a distance range 1-100 m. The measurements were carried out by using 2.4 GHz ZigBee wireless protocol based on XBee series 2 modules.

The results disclosed that the mean absolute error (MAE) of 3.44 and 6.72 m for a distance range 0-65 m and 0-100 m, respectively. These results point that the LNSM is only suited for short distance.

Keywords- Distance estimation, LNSM, RSSI, WSN, ZigBee

INTRODUCTION

Wireless Sensor Networks (WSNs) consist of several wireless nodes deployed in a large area that have the ability to sense different events based on the type of application. Most WSNs are using ZigBee wireless protocol in the framework of the network. This is because the ZigBee has the following advantages [1, 2]; (i) it works with low power consumption (ii) it enters in sleep mode to save energy, when there is no data ready for transmission, (iii) it transfers data between nodes in a WSN for monitoring and controlling systems [3, 4], (iv) it works with a free license ISM band 2.4 GHz radio frequency (RF), (v) data rate up to 250 kbps [5] for transferring data between ZigBee modules in WSN, (vi) the ZigBee protocol is based on the IEEE 802.15.4 standard known as a Low-Rate Wireless Personal Area Network (LR-WPAN). This protocol implements error detection, addressing, media access control, and acknowledgements and retries to ensure data delivery and integrity [3], and (vii) it is small size and light weight which in turns can be implanted in different sensor nodes.

In ZigBee network, the sensing environments can be achieved in a sensor node and transmitted through router node or directly to the coordinator node. The sensor nodes typically depict by low power consumption, low cost, and miniaturized size, which called as motes in the wireless sensor node applications [6]. A sensor node or mote is consists of four main parts: a sensing unit, data processing unit, communication unit, and power unit. The sensing unit converts a physical quantity into beneficial electrical signal. The processing unit collected, extracting, and process the signals of sensor elements. In addition, it performs the network

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protocols and determines the computing capabilities and the energy of a sensor node. The communication unit is responsible for establishing the communication between nodes of the network and communication with outside world. The power unit is supply the energy to the sensor nodes. The sensor nodes have limited resources such as memory size, power supply, communication range and computational capacity [7].

The RF transmitting signal is weakened by path loss or propagation channel. ZigBee radio modules support Received Signal Strength Indicator (RSSI) for each received data packet. The energy of a signal travelling between two nodes is the RSSI that contains information linked the distance between nodes in the network. The RSSI can be used together with path loss and shadowing model for distance estimation between nodes in the network [8]. In WSN application, awareness of the network channel model is necessary to estimate the nodes positions in the network. In addition, known the channel parameters such as path loss exponent and standard deviation can determine the type of channel environments.

The RSSI method is low cost [9] due to it is not need to (i) extra hardware, (ii) time synchronization, and (iii) antenna array, but not pointedly accurate. The RSSI method is often applied in WSN [10] to estimate the position of the nodes in the network based on distance measurement. In this application (i.e., mobile node), the mobile sensor node is restricted energy resources and hardware elements. Therefore, the RSSI method will be considered in this study. The RSSI measurement is significantly affected by the communication channel environments. Therefore, path loss model such as Log-Normal Shadowing Model (LNSM) will be used to estimate the distance between the mobile node and the coordinator node in ZigBee WSN based on RSSI measurements. The LNSM was considered in this paper because of its commonly used as wireless channel path loss model [11]. Moreover, it is widely used in several research works [12-15] as a channel model for indoor and outdoor environments to measure the distance between transmitter and receiver or to determine the location of the sensor node.

The contribution of this paper (i) to formulate a wireless channel path loss model for 2.4 GHz wireless channel in outdoor environments, (ii) A new path loss physical parameters (i.e., path loss exponents and standard deviation) related to the derived path loss model have been identified based on real measurements, and (iii) to measure the distance between mobile node and coordinator node based on derived path loss model in outdoor environments.

The rest of the paper as follows: Section 2 introduces the adopted wireless channel model, the configuration of the experiment will be presented in Section 3, Section 4 presents the results and discussions, and finally, Section 5 concludes the paper.

Wireless Channel Model based LNSM

Radio wave propagation happens when the wireless signal transmits in the air. The power of the transmitted signal will be attenuated by several parameters such as reflection, deflection, scattering, shadowing, and diffraction, which are the primary mechanisms that affect the propagation on the wireless channel [16]. Most wireless channel models are derived on the basis of a combination of analytical and practical methods [17]. The practical method has an advantage of taking into account the all propagation parameters in the channel [18]. Most wireless ZigBee modules support RSSI, which means, the received power can be measured for each received packet. The energy or power of a signal travelling between two nodes (i.e., a mobile node and coordinator node) is a signal parameter that includes information reflects the distance between these two nodes. This parameter can be used along with LNSM and path loss for distance estimation [19]. So, the LNSM can be given as [20].

$$PL(d) = PL_o + 10\gamma \, log_{10}\,(d/d_o) + \sigma \qquad \text{in dBm} \qquad \text{…. (1)}$$

Where

PL(d) is the path loss at a distance d in meters for outdoor, PL_o is the path loss at a reference distance d_o (1 meter) is recomended in several study such as [21-23] , PL_o can be obtained from Friis equation or field measurements, γ is the path loss exponent that points to the rate at which the RSSI decreases with distance, d is the distance between coordinator and mobile node in meters, it is change with mobile node 1-100 m, and σ is the standard deviation (in decibels). In this study, the parameters of the LNSM were measured practically through outdoor environments. The RSSI in dBm of the mobile node at the coordinator node can be calculated from the following equation.

$$RSSI = P_T - PL(d) \qquad \text{…. (2)}$$

where

P_T is the mobile node transmitted power in dBm (2 dBm adopted in this experiment). Then, the RSSI at the coordinator node will be [12, 15, 24-26]:

$$RSSI = P_T - PL_o - 10\gamma log_{10}\,(d/d_o) + \sigma \qquad \text{… (3)}$$

In this work, the RSSI of the ZigBee module can be obtained from real measurements and the γ and σ can be obtained from curve fitting. Therefore, the distance between the mobile node and the coordinator node can be estimated based on Equation (4), which obtained from Equation (3).

$$d = d_0 10^{-((RSSI-P_T+PL_0-\sigma)/10\gamma)} \qquad \text{…. (4)}$$

In this work, the theoritical values of; PL_o and d_o are 35 dBm (obtained from Friis equation for 2.4 GHz) and 1 m [21], assumed to be constant, respectively, the path loss exponent γ depends on the environment and can be varied between 2 - 6 for outdoor [27], and the standard deviation σ can be varied between 2 - 14 [12]. However, in this paper, the PL_o, path loss exponent, and standard deviation were measured practically.

Experiment Setup

To determine the chnnel model with related parameters (i.e., the path loss exponent and standard deviation), the experiment was conducted using point-to-point ZigBee WSN as shown in Figure 1. The experiment was carried out in an outdoor environment. The WSN consist of one coordinator node and one mobile node, both of them are height 1.5 m from the surface of the ground. The mobile node is moving away from the coordinator node until 100 m in predefined steps, each step is 5 m. The mobile node receives the data packets from the coordinator node and re-transmitted again to the coordinator node. The coordinator node receives the data packets of the mobile node and records the RSSI values in the laptop based on X-CTU software. In addition, the X-CTU software [28] can be used to configure and control the ZigBee (i.e., XBee series 2) module. The RSSI values were measured at 21 predefined locations including the measurements at 1 m. Twenty samples (each sample contains one data packet) were recorded at each location (Figure 2); each data packet contains 10 bytes. The twenty RSSI values were averaged in the coordinator node for each mobile node location.

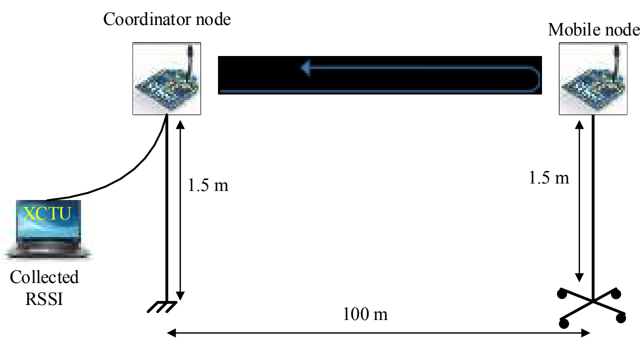

Figure (1). Point-to-point ZigBee WSN

Results and Discussions:

RSSI and Path Loss Measurements

The RSSI values were measured at twenty one locations, twenty samples in each location as shown in Figure 2. The RSSI values at each location were averaged as shown in Figure 2 as a black diamond points. The figure shows that the RSSI values have low variability from 1- 65 m, and high variability at a distance greater than 70 m. This is due to the path loss increases with respect to distance as shown in Figure 3. This figure discloses the attenuation due to free space in outdoor environments. The measured values were compared with the theoretical model (which is presented in Equation 1). Figure 3 shows the divergence between measured and theoretical plots increases with distance.

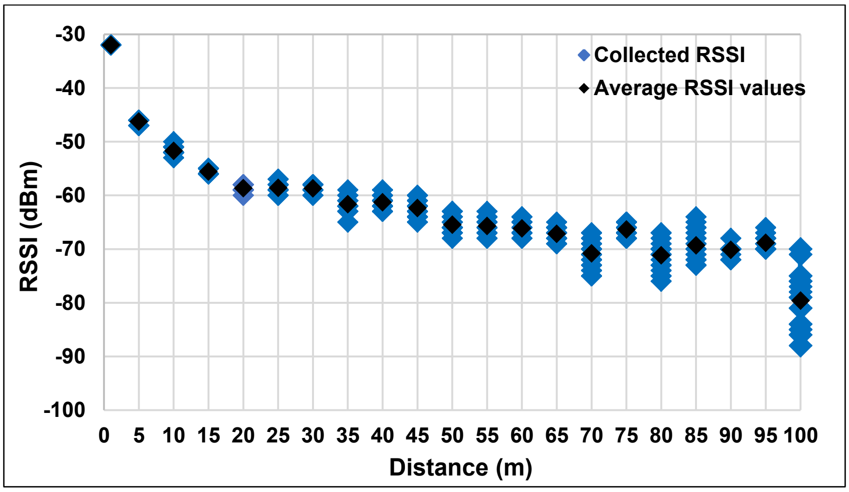

Figure (2). Collected RSSI values with respect to the distance

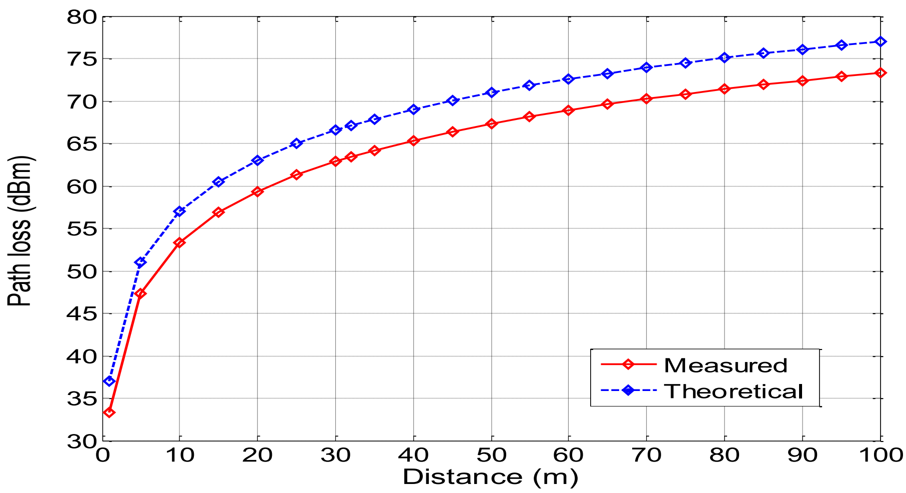

Figure (3) Path loss versus distance for outdoor environments

Theoretically, the RSSI attenuates with the square of the separation distance between transmitter and receiver. In this paper, the experiment is conducted to collect the measured values of RSSI. The X-CTU software is used to configure the XBees of coordinator and mobile nodes. In addition, it is used to measure the RSSI values of the mobile node and received data packets by the coordinator node. Figure 4 shows the measured and theoretical RSSI values and the percentage of the data packets received by the coordinator node for outdoor environments as a function of the distance between a mobile node and coordinator node.

A close agreement between measured and theoretical plots can be noticed in an outdoor environment. The theoretical plot is obtained based on Equation (3), whereas the measured plot is achieved based on real measurements. Figure 4 shows the percentage of data packets received by the coordinator node at different distances. However, the received packets are 100% - 97 % at less than 40 m, whereas it has fluctuated between 95% - 91% at greater than 45 m. This is due to the same reason of path loss increseas with distance.

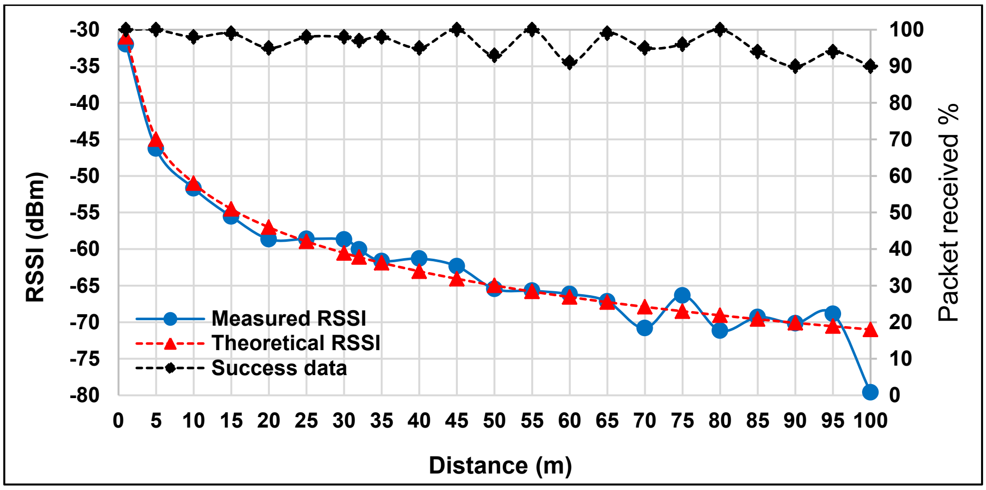

Figure (4) Measured and theoretical RSSI values and received data packet versus distance for outdoor environments.

LNSM Estimation Model

Based on the measurements of the averaged RSSI at predefined positions in outdoor environments, the LNSM model and related parameters can be estimated. A relationship between averaged RSSI values and logarithmic scale of predefined positions are plotted for outdoor environments to get the LNSM and related parameters as shown in Figure 5 and Table 1, respectively. The path loss exponent γ and standard deviation σ can be obtained by using the curve fitting in Figure 5. Therefore, the estimated regression line can be yielded the following equation.

$$RSSI(dBm) = -20.026Log(d/d_o) - 31.326 \quad \text{.... (5)}$$

Compare Equations 5 with Equation 3, the measured parameters of the LNSM can be obtained as shown in Table 1, where the transmitted power of the mobile node is 2 dBm.

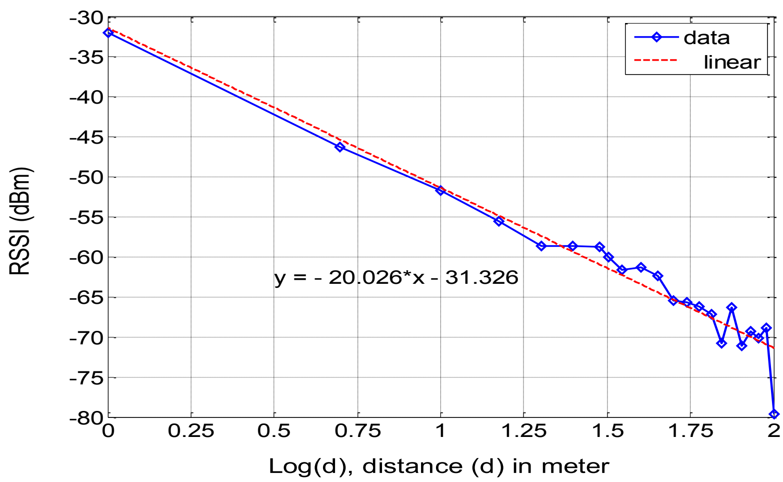

Figure (5) The curvefitting for outdoor environment

Table (1) Measured and Theoretical parameters of LNSM for outdoor environments

Parameters	Symbol	Outdoor Environments	
		Theoretical	Measured
Path loss exponent	γ	2	2
Standard deviation (dB)	σ	2	1.326
Reference distance (m)	d_o	1	1
Path loss at a distance d_o (dBm)	PL_0	35	32
Transmitter power (dBm)	P_T	2	2
Distance under test (m)	d	1-100	1-100

Errors and standard deviation estimation

Equations 4 can be used to estimate the distance under test for outdoor environments by substituting the obtained measured values (from Table 1) in Equation 4 or by rearranging Equation (5). In that case, Equation (6) will be yielded.

$$d = d_o 10^{-(RSSI+31.326)/20.026} \quad \text{(m)} \qquad \ldots. (6)$$

Based on equations 6 the measured distance can be obtained. The distance measurement error (e_i) can be calculated based on Equation (7).

$$e_i = d_r - d_m \qquad \ldots. (7)$$

Where

d_r is the real distance between the coordinator node and the mobile node, which calculated based on the conventional distance meter and d_m is the measured distance, which can be obtained from Equation (6). Consequently, the distance measurement error can be plotted as shown in Figure (6) relative to the real distance. The figure shows that the error increases with distance and vice versa, the error becomes higher after 65 m. The figure reveals that the adopted measurement method (i.e., RSSI based LNSM) is suitable for outdoor environment when the mobile node distance to the coordinator node is less than 65 m.

The standard deviation of RSSI measurement was investigated with respect to the distance as shown in Figure (7). The figure shows that the RSSI values are more deviated at greater than 65 m, this leads to a high distance measurement error occurs at a greater than this distance as seen in Figure (6). Thus, the results illustrated in Figure (7) are consistent with that one presented in Figure (6).

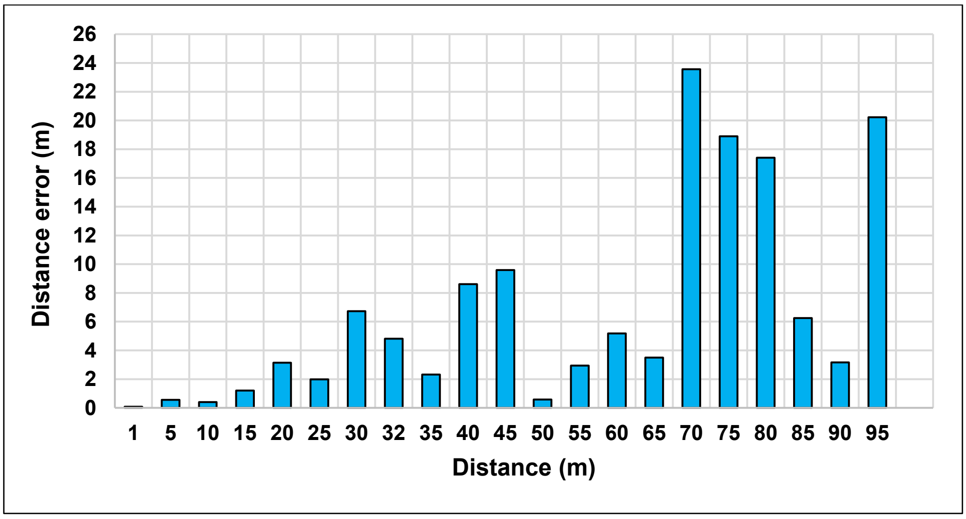

Figure (6) Error with respect to the distance

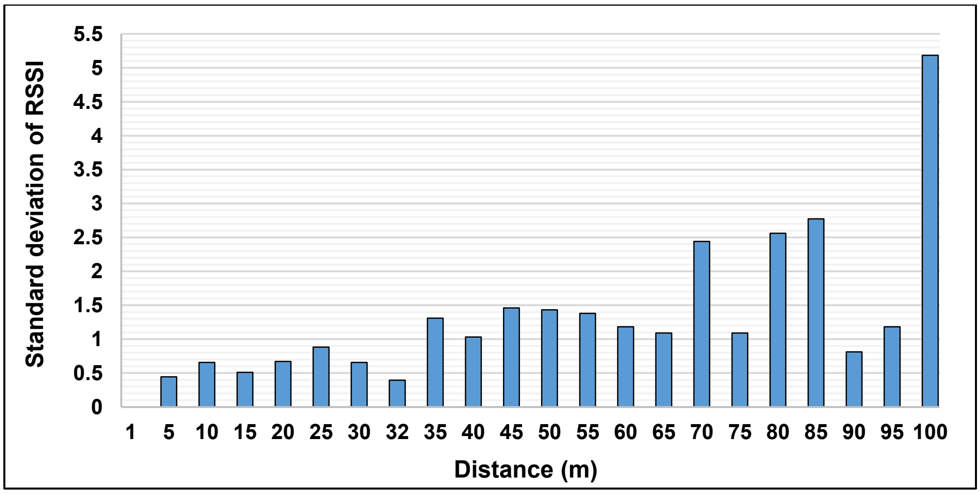

Figure (7). The standard deviation of the RSSI values with respect to the distance.

The correlation between the real distance and the measured distance was evaluated using a linear fit as shown in Figure (8). The results show that the correlation coefficients were R^2 = 0.8927 and R^2 = 0.9695 for the measured error (0-100) and (0-65), respectively. The correlation coefficient values indicate a high level of correlation between the real distance and measured distance in the range between (0-65 m).

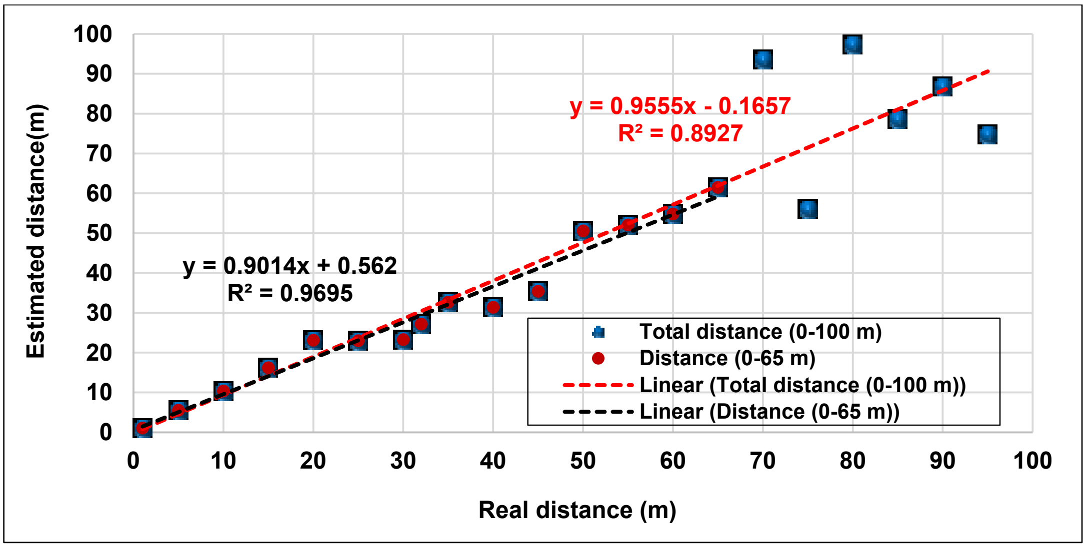

Figure (8) The correlation between real distance and measured distance (0-100m) and measured distance (0-65m)

MAE and RMSE

The error between the real distance and the measurement distance can be calculated based on MAE and RMSE. The MAE and RMSE, can be computed using Equation (8) and (9), respectively [29].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|e_i^2| \quad ....(8)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \quad \text{.... (9)}$$

Where

n is the number of samples of calculated error.

The MAE and RMSE error was obtained of 3.44 and 4.5 m from a distance in the range of (0-65m), respectively. The MAE and RMSE error was 6.72 and 9.48, for a distance in the range of (0-100 m), respectively as shown in Figure (8). However, when the distance in the range of (0-65m), the obtained distance error is better than in the range of (0-100).

The MAE and RMSE calculations reveal that the distance measurement using LNSM is to extant accurate for a short distance, whereas it was not appropriate for application with a long distance.

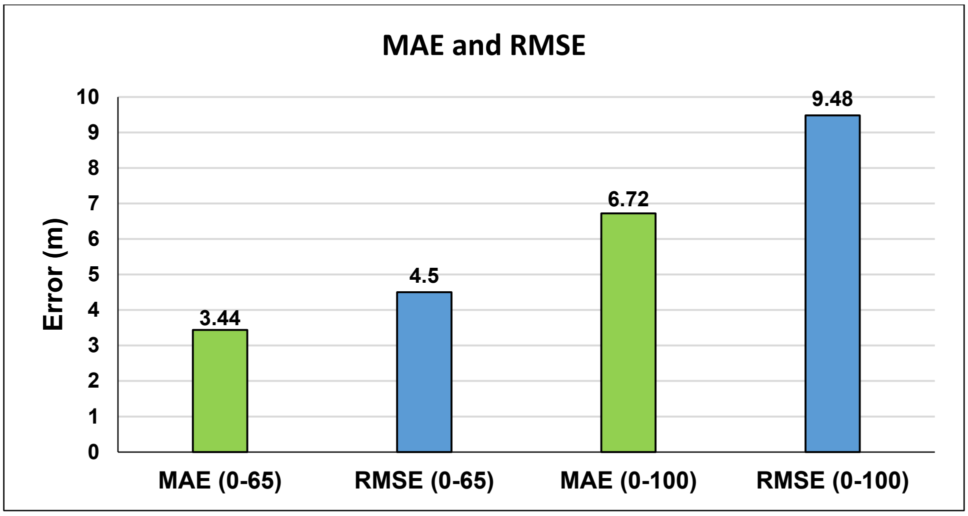

Figure (9). MAE and RMSE for measured distance (0-100m) and measured distance (0-65m).

CONCLUSIONS

In this paper, the RSSI values for ZigBee mobile node was used to measure the distance between ZigBee mobile node and ZigBee coordinator node in outdoor environments. A linear fit relationship between RSSI values in decibels and different distance in meters was established to derive an outdoor path loss model based on LNSM. In addition the channel parameters such as standard deviation and a path loss exponent were measured. XBee Series 2 wireless technology was employed in this study because it has the capability of RSSI measurements without extra hardware, low cost, low complexity, and low power consumption.

The standard deviation of RSSI measurements was examined with respect to the different distance between mobile node and coordinator node. The standard deviation was higher in the range of 65-100 m relative to the range of 0-65 m. For that reason, the RSSI deviation increases with distance. The correlation coefficient, MAE and RMSE were used to evaluate the distance estimation error between mobile node and coordinator node. The correlation between the real distance and the measured distance was evaluated using a curve fitting relationship. The results show that the correlation coefficient for distance 0-65 m is better than the distance in the range of 0-100 m. Furthermore, the result was promising for less than 65 m, where the MAE was 3.44 m and RMSE of 4.5 m. This work can be extended in future work by using an accurate distance estimation method such as artificial neural network (NN) or by combining two artificial intelligence methods. Thereby, the application may be used in indoor environments.

REFERENCES

[1] S. Gharghan, R. Nordin, and M. Ismail, "An Ultra-Low Power Wireless Sensor Network for Bicycle Torque Performance Measurements," Sensors, vol. 15, p. 11741, 2015.
[2] S. Gharghan, R. Nordin, and M. Ismail, "Energy-Efficient ZigBee BasedWirelessSensor Network for Track Bicycle Performance Monitoring," Sensors, vol. 14, p. 15573, 2014.
[3] M. Hebel and G. Bricker, "Getting Started with XBee RF Modules," Parallax inc, p. 30.
[4] C. Bell, Beginning Sensor Networks with Arduino and Raspberry Pi: Apress, 2013.
[5] M. Di Francesco, G. Anastasi, M. Conti, S. K. Das, and V. Neri, "Reliability and Energy-Efficiency inIEEE 802.15.4/ZigBee Sensor Networks:An Adaptive and Cross Layer Approach," Selected Areas in Communications, IEEE Journal on, vol. 29, pp. 1508-1524, 2011.
[6] N. S. Kulkarni, R. Rakesh, S. Bhargava, S. S. Bundela, and R. Hegde, "Zigbee based low power wireless sensor network motes," in International Conference on Next Generation Networks, 2010, pp. 1-6.
[7] A. B. da Cunha and D. C. da Silva Jr, "An approach for the reduction of power consumption in sensor nodes of wireless sensor networks: Case analysis of mica2," in Embedded Computer Systems: Architectures, Modeling, and Simulation, ed: Springer, 2006, pp. 132-141.
[8] M. Malajner, K. Benkič, P. Planinšič, and Ž. Čučej, "The accuracy of propagation models for distance measurement between WSN nodes," in 16th International Conference on Systems, Signals and Image Processing, 2009, pp. 1-4.
[9] R. Al Alawi, "RSSI based location estimation in wireless sensors networks," in 17th IEEE International Conference on Networks (ICON), 2011, pp. 118-122.
[10] F. Liu, H. Zhu, Z. Gu, and Y. Liu, "A Linear Localization Algorithm for Wireless Sensor Network Based on RSSI," in Advanced Research on Computer Education, Simulation and Modeling. vol. 176, S. Lin and X. Huang, Eds., ed: Springer Berlin Heidelberg, 2011, pp. 384-389.
[11] J. Xu, W. Liu, F. Lang, Y. Zhang, and C. Wang, "Distance Measurement Model Based on RSSI in WSN," Wireless Sensor Network, vol. 2, pp. 606-611, 2010.
[12] K. S. Pratap, H.-K. W. Eric, and S. Jagruti, "DuRT: Dual RSSI Trend Based Localization for Wireless Sensor Networks," IEEE Sensors Journal vol. 13, pp. 3115 3123, 2013.
[13] F. Shang, W. Su, Q. Wang, H. Gao, and Q. Fu, "A Location Estimation Algorithm Based on RSSI Vector Similarity Degree," International Journal of Distributed Sensor Networks, vol. 2014, 2014.
[14] X. Yaming, Z. Jianguo, and Z. Peng, "RSS-Based Source Localization When Path Loss Model Parameters are Unknown," IEEE Communications Letters, vol. 18, pp. 1055-1058, 2014.
[15] L. Tang, M. Liu, K.-C. Wang, Y. Huang, F. Yang, and D. Zhang, "Study of path loss and data transmission error of IEEE 802.15.4 compliant wireless sensors in small scale manufacturing environments," The International Journal of Advanced Manufacturing Technology, vol. 63, pp. 659-669, 2012.
[16] H. Li, L. Zhao, M. J. Darr, and P. Ling, "Modeling Wireless Signal Transmission Performance Path Loss for ZigBee Communication Protocol in Residential Houses," in In Presentation at 2009 ASABE Annual International Meeting, 2009.
[17] O. Musikanon and W. Chongburee, "ZigBee propagations and performance analysis in last mile network," International Journal of Innovation, Management and

Technology, vol. 3, pp. 353-357, 2012.
[18] O. Musikanon and W. Chongburee, "ZigBee propagations and performance analysis in last mile network," Int. J. Innov. Manag. Technol, vol. 3, pp. 353-357, 2012.
[19] M. Malajner, K. Benkic, P. Planinsic, and Z. Cucej, "The accuracy of propagation models for distance measurement between WSN nodes," in IEEE 16th International Conference on Systems, Signals and Image Processing (IWSSIP), 2009, pp. 1-4.
[20] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, MIMO-OFDM wireless communications with MATLAB: John Wiley & Sons, 2010.
[21] H. Cotuk, K. Bicakci, B. Tavli, and E. Uzun, "The impact of transmission power control strategies on lifetime of wireless sensor networks," IEEE Transactions on Computers, vol. 63, pp. 2866-2879, 2014.
[22] S. Kim and D.-S. Eom, "Distributed Transmission Power Control for Network Programming in Wireless Sensor Networks," Wireless personal communications, vol. 72, pp. 1533-1548, 2013.
[23] L. Cheng, C.-D. Wu, and Y.-Z. Zhang, "Indoor robot localization based on wireless sensor networks," IEEE Transactions on Consumer Electronics, vol. 57, pp. 1099 1104, 2011.
[24] X. Ta, G. Mao, and B. D. Anderson, "On the giant component of wireless multihop networks in the presence of shadowing," IEEE Transactions on Vehicular Technology, vol. 58, pp. 5152-5163, 2009.
[25] P. K. Sahoo and I. Hwang, "Collaborative localization algorithms for wireless sensor networks with reduced localization error," Sensors, vol. 11, pp. 9989-10009, 2011.
[26] J. Zhao, W. Xi, Y. He, Y. Liu, X.-Y. Li, L. Mo, et al., "Localization of wireless sensor networks in the wild: Pursuit of ranging quality," IEEE/ACM Transactions on Networking (TON), vol. 21, pp. 311-323, 2013.
[27] T. Xiaoyuan, M. Guoqiang, and B. D. O. Anderson, "On the Giant Component of Wireless Multihop Networks in the Presence of Shadowing," IEEE Transactions on Vehicular Technology, vol. 58, pp. 5152-5163, 2009.
[28] K.-Y. Lian, S.-J. Hsiao, and W.-T. Sung, "Intelligent multi-sensor control system based on innovative technology integration via ZigBee and Wi-Fi networks," Journal of Network and Computer Applications, vol. 36, pp. 756-767, 2013.
[29] T. Chai and R. R. Draxler, "Root mean square error (RMSE) or mean absolute error (MAE)?–Arguments against avoiding RMSE in the literature," Geoscientific Model Development, vol. 7, pp. 1247-1250, 2014.