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Distance-based Indoor Localization System Utilizing General Path Loss Model and RSSI

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Abstract*— Wireless sensor networks (WSNs) have a vital role in indoor localization development. As today, there are more demands in location-based service (LBS), mainly indoor environments, which put the researches on indoor localization massive attention. As the global-positioning-system (GPS) is unreliable indoor, some methods in WSNs-based indoor localization have been developed. Path loss model-based can be useful for providing the power-distance relationship the distance-based indoor localization. Received signal strength indicator (RSSI) has been commonly utilized and proven to be a reliable yet straightforward metric in the distance-based method. We face issues related to the complexity of indoor localization to be deployed in a real situation. Hence, it motivates us to propose a simple yet having acceptable accuracy results. In this research, we applied the standard distance-based methods, which are is trilateration and min-max or bounding box algorithm. We used the RSSI values as the localization parameter from the ZigBee standard. We utilized the general path loss model to estimate the traveling distance between the transmitter (TX) and receiver (RX) based on the RSSI values. We conducted measurements in a simple indoor lobby environment to validate the performance of our proposed localization system. The results show that the min-max algorithm performs better accuracy compared to the trilateration, which yields an error distance of up to 3m. By these results, we conclude that the distance-based method using ZigBee standard working on 2.4 GHz center frequency can be reliable in the range of 1-3m. This small range is affected by the existence of interference objects (IOs) lead to signal multipath, causing the unreliability of RSSI values. These results can be the first step for building the indoor localization system, which low-cost, low-complexity, and can be applied in many fields, especially indoor robots and small devices in internet-of-things (IoT) world's today.

Keywords—indoor localization, distance-based, path loss model, RSSI, trilateration, min-max

I. INTRODUCTION

We use location-based service (LBS) everywhere nowadays. As the smartphone provides the current location point, some benefits, including the advertisement, interesting places nearby, the marketplace, and others, can be fitted based on the location. Many emerging companies, and even some disruptive business giants, use the user locations as the essential data for their marketing point-of-view [1][2][3]. Most of the LBS utilization now relies on how the global positioning system (GPS) provides the exact location of the user. It is reliable only for outdoor, in the indoor environment, which is more complicated with many of interference objects (IOs) in such a small space, the propagation mechanism leads to positioning error for the GPS signal [4]. Thus, the indoor localization by using another setup and system is needed to be considered [5].

Wireless sensor networks (WSNs) offer the indoor localization application in ease, especially when the simple and acceptable accuracy of the system is emphasized [6] [7]. Two main indoor localization methods draw much attention; distance-based and fingerprint-based [8]. The distance-based is a simple method employing the parameters which lead to the distance of the transceiver. This distance can help locate the target by using the trilateration method [9]. This distance parameter in wireless can simply use the path loss model in a specific location [10]. The path loss model is a model that represents the power-distance relationship of the transmitter (TX) and receiver (RX). This power in the RX describes the received signal strength indicator (RSSI) [11]–[13].

Fingerprint technique, on the other hand, is using this RSSI to collect the database for the "radio fingerprint." By collecting an extensive database of RSSI in a precise position (coordinates), the target position is matched by the component of RSSI of the target and the database [14], [15]. Even though this technique provides a reliable accuracy compared to the distance-based, the high and lengthy effort to collect the fingerprint database becomes the first drawback of this method. Besides, the fingerprint database recorded is a site-specific database [16]. Meaning that if there is a case using a fingerprint technique in other indoor environments, the collection of a new database needs to be done [17].

Many papers discuss the importance and how it less-complex in the usage of the RSSI parameter for indoor localization [5], [18], [19]. Some papers also mention that by using the RSSI, the accuracy of the target positioning is acceptable [11], [20], [21]. This parameter can be easily applied and obtained by using several wireless devices, such as Wi-Fi-based devices, ZigBee standards, and others. These devices mostly operate in the 2.4 GHz band, which is also a free band for educational purposes. However, the signal distraction due to the overuse of this frequency spectrum can lead to inaccuracy results [7].

In this paper, we consider applying the ZigBee standard for obtaining the RSSI for our proposed indoor localization systems [22]. As the concept of WSNs, we define the nodes in two categories; sensor nodes or reference nodes and a target node. Both sensors and target nodes consist of three main components, which are sensing, processing, and communication [22]. The target node acts as the transceiver, which broadcasts the signal which is received by sensor nodes, processed it, and finally sent back to the target node in the form of RSSI. We apply the WSNs star topology for this communication procedure.

We employ the path loss model provided by the ZigBee standard to relate the RSSI for the sensor-target distance [23]. The path loss exponent is obtained by field measurement in a site-specific lobby environment where we conduct the measurement. We consider the 4-sensor nodes in a rectangular-shape, with the target node is inside the area of interest of 5m-by-5m in the 1m grid. We apply the trilateration and min-max method as the distance-based method. The measurement is conducted extensively, and we designed the location of the target as the accuracy location validation.

Our results show that by using the trilateration and min-max method as the distance-based method in our indoor localization, the accuracy is acceptable and reliable within certain distances. We found that a distance of more than 3m can lead to error in target position estimation. The min-max algorithm shows superior performance compared to trilateration methods. In fact, due to the bounding box estimation, the estimated target location more reliable compared to only using a power-distance relationship. In which, the received powers become inaccurate because of signal propagation effect due to interference objects (IOs) in the indoor environment. These preliminary results also show that indoor localization can be applied and further enhanced, especially for robot or small devices localization. Furthermore, the results can be a solution in providing the small-space indoor localization using a commercial and low-cost system.

We organize the finding as follows; we presented the introduction in the first section, the indoor localization with the detail of its method is presented in the 2nd section followed by the empirical path loss model and RSSI in the 3rd section. We detailed the measurement campaign in section 4. We provide the preliminary conclusion and our plan for the future work in section 5.

II. INDOOR LOCALIZATION

Many researchers have proposed many methods to achieve an accurate and reliable WSNs-based indoor localization. In distance or range-based localization, several methods including path signal power utilizations, i.e., RSSI, an angular method such as angle-of-arrival (AoA), time-of-arrival (ToA) and time difference-of-arrival (TDoA) as signal time-based method have been well published [24]. Distance-free localization method such as pattern-matching or fingerprint localization draws much attention in indoor localization. Fig. 1 show the diagram of the WSNs-based indoor localization methods.

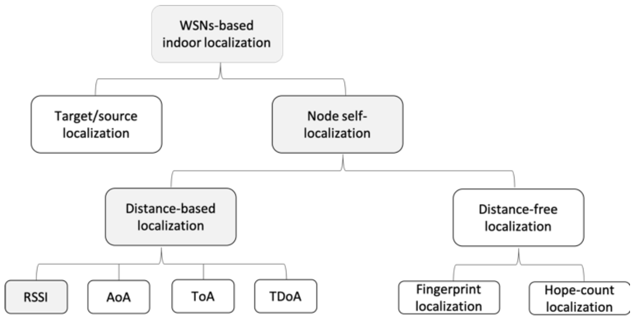

Fig. 1. Taxonomy of WSNs-based indoor localization [19].

In this research, we emphasize in the node self-localization, where the low-cost and low-complexity hardware and software setup development to provide the RSSI parameter for distance-based indoor localization. RSSI utilizes the path loss model which relatively simple and straightforward.

A. Trilateration

The trilateration method needs at least 3 (three) reference distance to locate the position of the object or target. In WSNs, we applied the star topology, in which the sink/communication node acts as the target and the sensor nodes that communicating to the sink node act as the reference [6], [8], [25]. The arrangement of the system can be illustrated as Fig. 2 with Ref. 1, 2, and 3 are reference nodes/devices. Reference distances are obtained from sink node then processed it by a data processor.

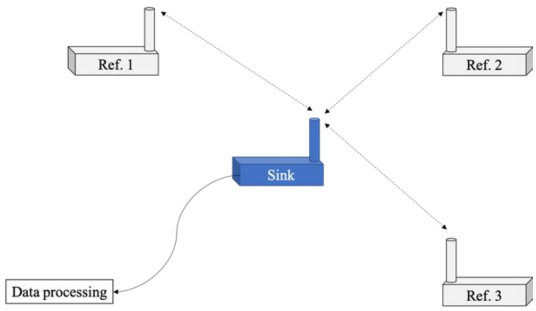

Fig. 2. General illustration of WSNs-based trilateration method.

For the mathematical expression explanation, Fig. 3 illustrates the trilateration method used in this research.

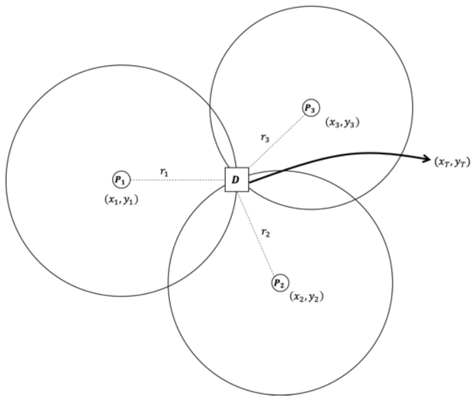

Fig. 3. Illustration of the trilateration method.

P_1, P_2, and P_3 are the reference nodes to form the reference distance of the target/object. From the circle equation, we can find the values of r_1, r_2, and r_3.

$$(x-x_1)^2+(y-y_1)^2=r_1^2 \quad (1)$$
$$(x-x_2)^2+(y-y_2)^2=r_2^2 \quad (2)$$
$$(x-x_3)^2+(y-y_3)^2=r_3^2 \quad (3)$$

We can rewrite the eq. (1-3) as

$$x^2-2x_1x+x_1^2+y^2-2y_1y+y_1^2=r_1^2 \quad (4)$$
$$x^2-2x_2x+x_2^2+y^2-2y_2y+y_2^2=r_2^2 \quad (5)$$
$$x^2-2x_3x+x_3^2+y^2-2y_3y+y_3^2=r_3^2 \quad (6)$$

By subtracting the eq. (4) to eq. (5) and eq. (5) to eq. (6), we get

$$(-2x_1+2x_2)x+(-2y_1+2y)y = r_1^2-r_2^2-x_1^2-x_2^2-y_1^2-y_2^2 \quad (7)$$

$$(-2x_2+2x_3)x+(-2y_2+2y_3)y = r_2^2-r_3^2-x_2^2-x_3^2-y_2^2-y_3^2 \quad (8)$$

We can simplify the eq. (7) and eq. (8) so that

$$Ax+By=C \quad (9)$$
$$Dx+Ey=F \quad (10)$$

From the eq. (9) and eq. (10) we can simply apply the matrix relationship so that the position of the target node in x and y can be estimated [18].

$$x=\frac{CE-BF}{AE-BD} \quad (11)$$

$$y=\frac{CD-AF}{BD-AE} \quad (12)$$

B. Min-Max Algorithm

The idea behind the min-max algorithm or bounding-box is to find the target location at a certain point of the rectangular intersection [26]–[28]. This rectangular is shaped from the circle with radius, r which, in this research, is the distance calculated from RSSI values.

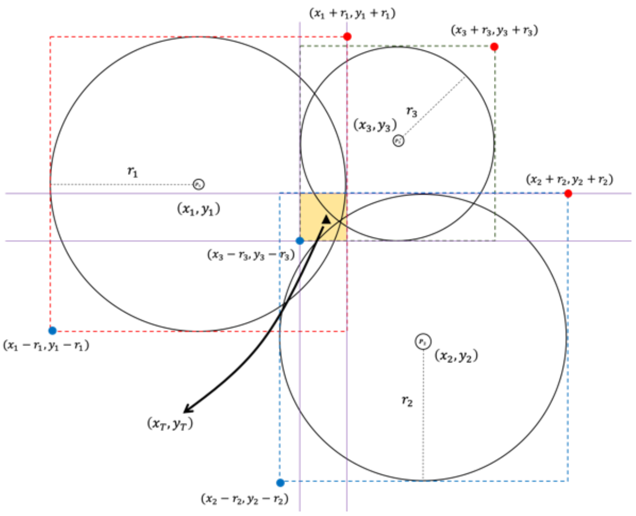

Fig. 4. Illustration of min-max method.

Fig. 4 depicts the illustration of the min-max algorithm. To obtain the estimated position of the target node, firstly, the bounding boxes are formed. The number of these boxes depends on the number of reference nodes employed. The bounding box is obtained by adding the coordinates of the reference node with the radius of the corresponding circles, r_i, with $i=1,2,3\ldots\ldots,N$.

Given, the maximum and minimum coordinates as the column vector:

$$\boldsymbol{x_{max}}=\begin{bmatrix}x_1+r_1\\x_2+r_2\\\vdots\\x_N+r_N\end{bmatrix} \quad (13)$$

$$\boldsymbol{x_{min}}=\begin{bmatrix}x_1-r_1\\x_2-r_2\\\vdots\\x_N-r_N\end{bmatrix} \quad (14)$$

$$\boldsymbol{y_{max}}=\begin{bmatrix}y_1+r_1\\y_2+r_2\\\vdots\\y_N+r_N\end{bmatrix} \quad (15)$$

$$\boldsymbol{y_{min}}=\begin{bmatrix}x_1-r_1\\x_2-r_2\\\vdots\\x_N-r_N\end{bmatrix} \quad (16)$$

From the definition, min-max represents the minimum values of the maximum vector coordinates and inversely, max-min is maximum values of minimum vector coordinates. From this, the coordinates of min-max and max-min can be expressed as

$$x_{minmax} = \min_{x_i+r_i} \boldsymbol{x_{max}} \quad (17)$$

$$x_{maxmin} = \max_{x_i-r_i} \boldsymbol{x_{min}} \quad (18)$$

$$y_{minmax} = \min_{y_i+r_i} \boldsymbol{y_{max}} \quad (19)$$

$$y_{maxmin} = \max_{y_i-r_i} \boldsymbol{y_{min}} \quad (20)$$

Thus, the location of the target node, x_T and y_T can be presented as the center coordinates of $x_{min-max}$ and $x_{max-min}$ and the center coordinates of $y_{min-max}$ and $y_{max-min}$.

$$x_T=\frac{x_{minmax}+x_{maxmin}}{2} \quad (21)$$

$$y_T=\frac{y_{minmax}+y_{maxmin}}{2} \quad (22)$$

III. EMPIRICAL PATH LOSS AND RSSI

A. Path Loss Model

The generic path loss model is used to show the relationship between power and the traveling distance of the signal [29], [30].

$$P_r = P_t K \left[\frac{d_0}{d}\right]^n \quad (23)$$

Eq. (23) shows the generic path loss model representing the relationship between received power, P_r, transmit power, P_t, K is free-space path loss, d_0 is a reference distance, typically 1m, d is the distance between transmitter and receiver (traveling distance), and n is the path loss exponent. Eq. (24) expresses the Eq. (23) in dB format as [19]

$$P_r\ (dBm) = P_t\ (dBm) + K\ (dB) - 10n log_{10}\left[\frac{d}{d_0}\right] \quad (24)$$

B. RSSI

Received signal information is an essential parameter and mostly used for the simple setup of the indoor localization system. RSSI represents the relationship between received and transmit power [30].

$$RSSI = \frac{P_r}{P_t} \quad (25)$$

RSSI expressed in dB is

$$RSSI\ (dBm) = P_r(dBm) - P_t(dBm) \quad (26)$$

C. Path Loss and RSSI

The path loss empiric model used in this research is,

$$RSSI = -10n \log_{10}(d\ ) + A \quad (27)$$

Eq. (27) represents the path loss model for the XBee module [20], [27]. With A represents the RSSI value in the 1m-reference point (similar presentation of K). If d equals to the radius of i^{th}circle in the previous subsection, r_i, by using eq. (28) we can estimate the corresponding distance of the target for the reference i.

$$r_i = 10^{\left(\frac{A-RSSI}{10n}\right)} \quad (28)$$

We obtained the value of n by an theoretical iterative values from $n = 1, \ldots, 4$, and compared by plotting these results to the real RSSI from measurement values. We compared the root-mean-square error (RMSE) values of the RSSI values from theoretical and empirical/measurement of 4-reference nodes and took the lowest error as the n value for the considered indoor environment for measurement campaign.

For the value of A, we simply placed the TX-RX in 1m distance in a circle form. By doing this, we collected the value in each 45^0 and recorded the RSSI values. We collected the values for all 4-reference nodes and utilized the average value as the A value. Table 1 shows the value of n and A used for the analysis.

TABLE I. PATH LOSS PARAMETER

Path loss parameter	
Parameter	***Values***
Indoor path loss exponent, n	2.65
RSSI in 1m, A (dBm)	-32.85

IV. MEASUREMENT CAMPAIGN

We conducted field measurement in the lobby of the Department of Computer Engineering, KMITL. The field measurement, including the essential steps to obtain RSSI parameters from the empirical path loss values.

A. Measurement Detail

We employed the ZigBee standard, XBee-24ZB module, as the core of the indoor localization system [31], [32]. Table 2 presents the detail of the measurement system and setup.

TABLE II. MEASUREMENT CAMPAIGN

Parameters		
Site/equipment	***Descriptions***	***Detail***
Indoor lobby as area of interest	5m-by-5m, 1m grid	Assumption: no interference objects (IOs)
WSNs Hardware	ZigBee (XBee 24-ZB series)	2.4 GHz working frequency, battery powered.
WSNs Topology	Star	1 node for communication/target node, 4 nodes for reference nodes.
Software	Python 3.7.4	Self-built, license-free

1) Area of Interest

The measurements were conducted in a simple lobby environment where we expected the minimum IOs. Fig. 5 shows the real area of interest used in this measurement.

Fig. 5. Lobby environment for measurement campaign.

The card box seen in Fig. 5 is used as the placement of the 4 sensor nodes. We used a thin fabric to make a grid for target node placement and RSSI values collection. We placed the target node in a certain position to validate the robustness of the proposed indoor localization analysis method. The illustration of the measurement campaign is depicted in Fig. 6.

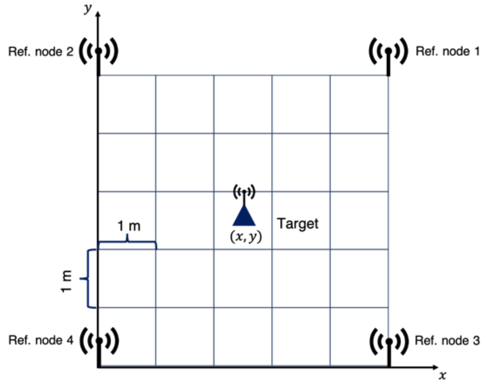

Fig. 6. Illustration of measurement layout.

Target is illustrated as triangle-shape with an antenna symbol. Reference node 1-4 are seen as the antenna symbol.

2) Star Topology and RSSI module: XBee-24ZB.

The star topology comprises of the one coordinator and some end devices [21]. In our approach, the sink node acts as the coordinator while the sensor nodes as the end devices. We employ XBee-24ZB as the sink node and the sensor nodes in the star topology scenario as illustrated in Fig. 7.

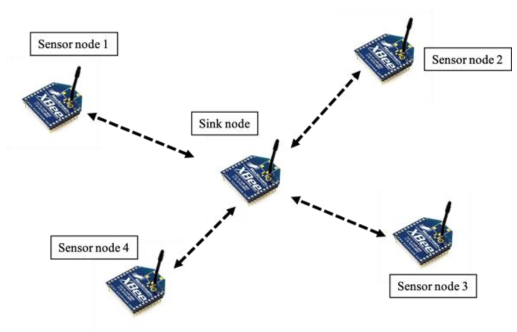

Fig. 7. Star topology.

This coordinator receives a command from the user by using personal computer (PC) and sends the specific request to the end devices, i.e., RSSI request. The end devices broadcast the RSSI data from XBee stack and send back to the coordinator.

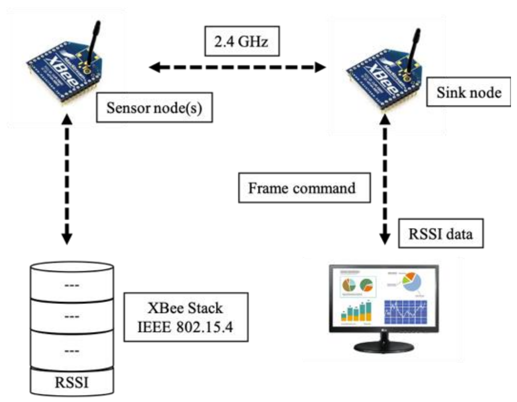

Fig. 8. Obtaining RSSI data from XBee stack.

The applicable programming interface (API) in the coordinator node (sink node) received a command from the user from the personal computer (PC) to sensor nodes. In the sensor node's perspectives, it took the RSSI value based on this command from the XBee stack. This communication is based on the IEEE 802.15.4 standard. Sensor nodes then send the RSSI values to the sink node. Finally, the RSSI data can be accessed from the received API frame[17].

B. *Validation of Localization Methods*

For our approach, indoor localization is not applied in real-time, yet. We recorded the RSSI values to analyze the location estimation by using the distance-based method.

1) Target node location

The target location is placed in a variation for the validation of the sensor nodes arrangement. Fig. 9 depicts the 4 (four) types of target node placement. Type 1 and 2 represent the diagonal placement while the Type 3 and 4 consider the horizontal and vertical placement in the area of interest [33].

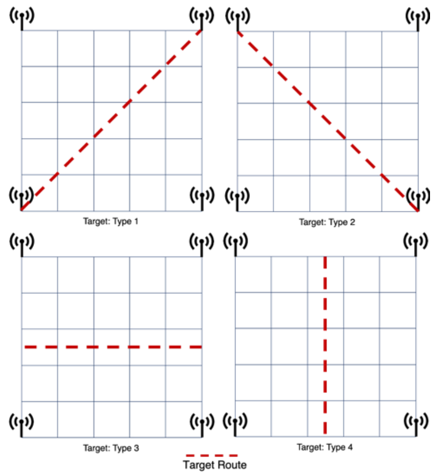

Fig. 9. Types of target node placement.

2) Breakdown node for triangle position

For the reference nodes, we propose the breakdown of four reference nodes to 4 (four) triangle positions for each combination of three nodes. These triangle positions of reference nodes is shown in Fig. 10.

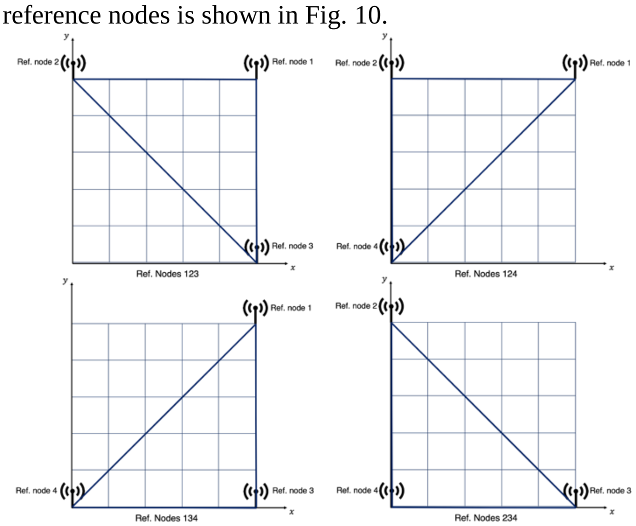

Fig. 10. Types of triangle position for proposed method.

The fundamental reason to have 3 (three) reference nodes is to apply the trilateration method in which need 3 reference points to estimate the target or object position. The min-max algorithm will also use the minimum-maximum values formed from the 3 reference points. We then validate these reference nodes arrangement performance by testing the target location as depicted in Fig. 9.

V. RESULTS AND DISCUSSION

We present the result in the comparison of validation results of each type position of the target node to the 4-triangle configuration of the reference nodes for both the trilateration method and the min-max algorithm, respectively.

A. *Trilateration Method*

1) *Target: Type 1*

The result of the estimated position by employing the trilateration method for target position type 1 is depicted in Fig. 11. The Ref. Nodes 234 show inaccuracy estimated position (orange dots) for all the real position of the target node (blue dots). On the other hand, 3 other Ref. Nodes type show similar trends.

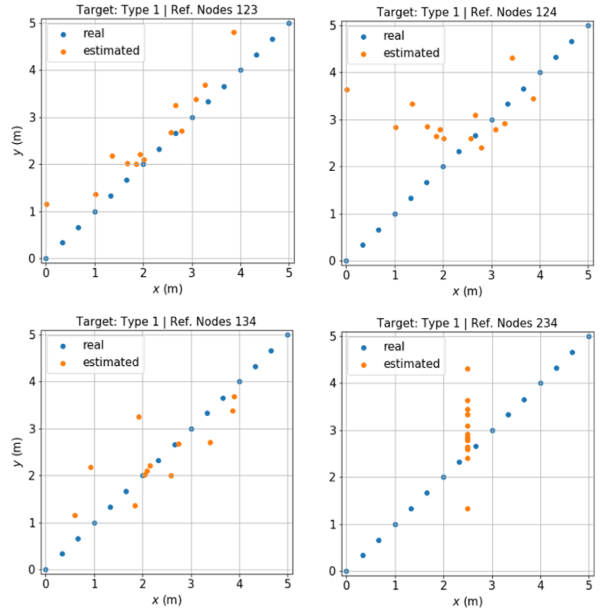

Fig. 11. Results of Target: Type 1 for trilateration method.

2) *Target: Type 2*

Target Type 2 is similar with the Type 1, only it is in a reverse direction of the diagonal position. As the position similar, we expect that the results will be similar to Fig. 11. Fig. 12 proves that the diagonal position gives some interesting findings, especially when the reference used is Ref. Nodes 234, we found that the estimation position accuracies are poor. In fact, it might the effects of the position of reference nodes. As observed in Fig. 10, the reference node 2 and 3 slice the left diagonal position in Ref. Nodes 123 and Ref. Nodes 234.

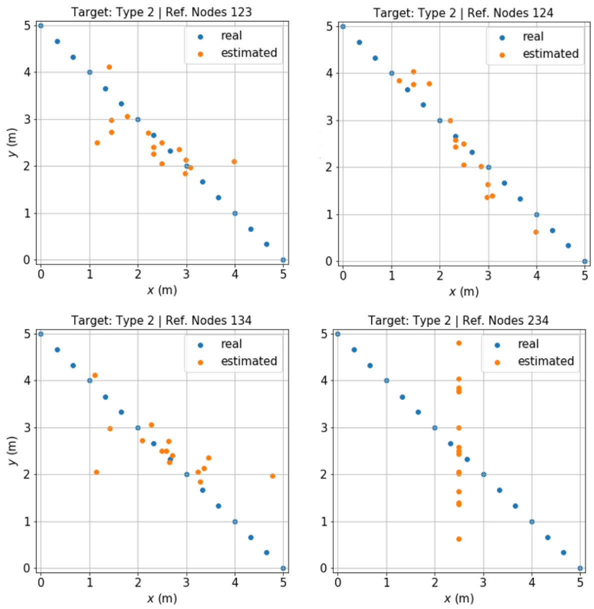

Fig. 12. Results of Target: Type 2 for trilateration method.

3) *Target: Type 3*

We obtained a similar results for target position Type 3 for Ref. Nodes 234. However, we find that the Ref. Nodes 124 also gives poor estimated results as nodes 1 and 2 are located close to the edge of the lobby room in the area of interest. The Ref. Nodes 123 and 134 give slightly better estimated position compared to 124 and 234. We analyzed that if there are two reference nodes in the right side of the triangle, for the target position in the horizontal position will give the better scalability to improve the accuracy results.

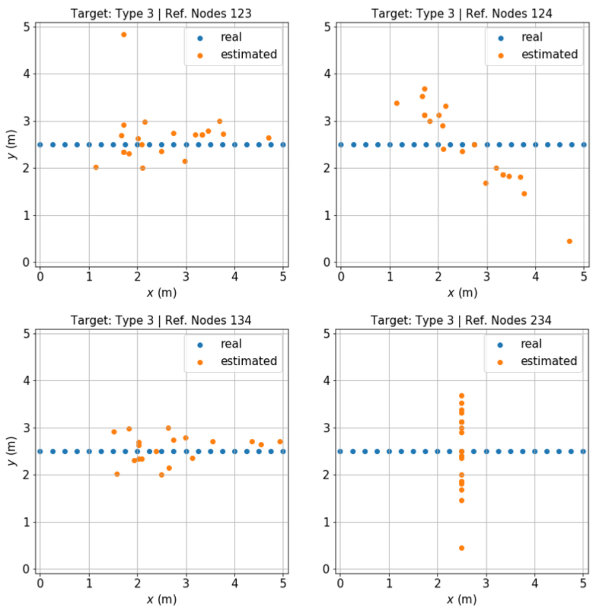

Fig. 13. Results of Target: Type 3 for trilateration method.

4) *Target: Type 4*

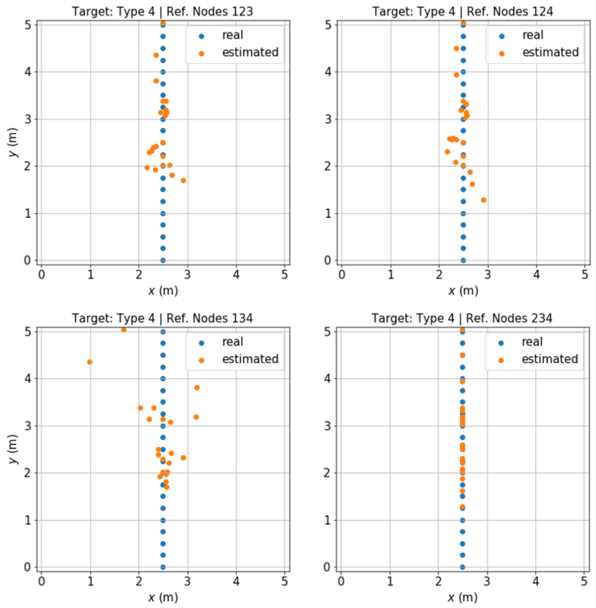

Fig. 14. Results of Target: Type 4 for trilateration method.

Finally, in the target position Type 4, we obtain better accuracy for all the positions of the target node. We conclude that the values of RSSI in the Ref. Nodes 234 is inconsistent due to the shadowing of the wall [34]. Furthermore, the triangle arrangement of the reference nodes plays an essential role in which the target is located.

B. *Min-Max Method*

The idea behind the min-max method or bounding box is to minimize the estimated error position by building a box in the circle associated with the distance.

1) *Target: Type 1*

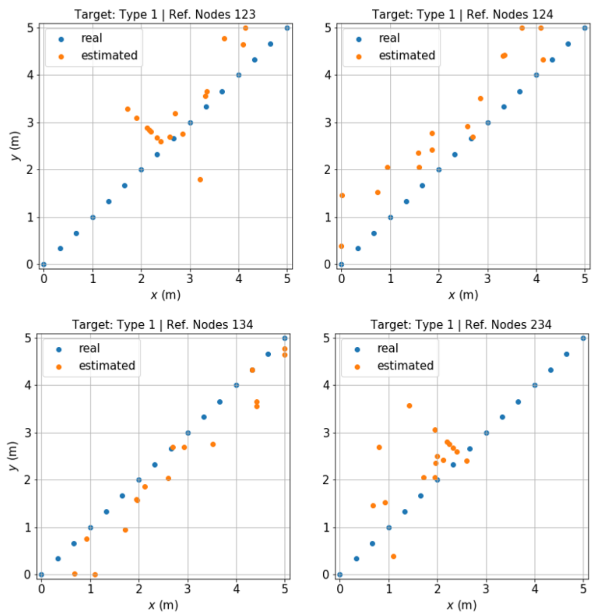

Fig. 15. Results of Target: Type 1 for min-max method.

Fig. 15 depicts the indoor localization results for target position Type 1. Compared to Fig. 11 in the trilateration method, there are improvements in the estimated location, especially in Ref. Nodes 234.

2) *Target: Type 2*

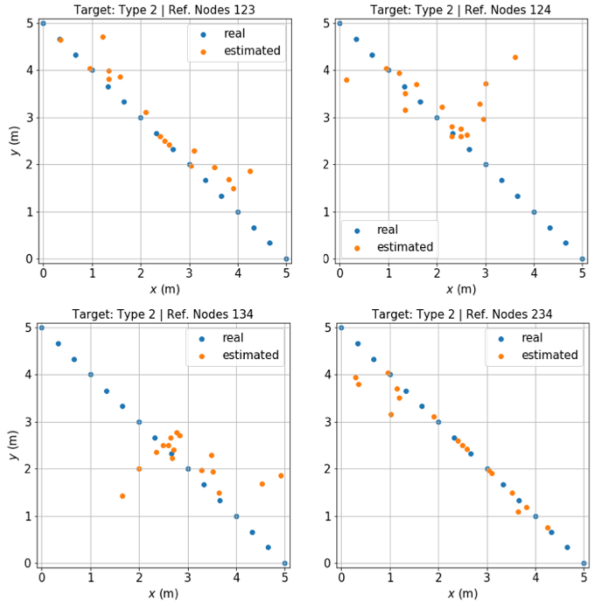

Fig. 16. Results of Target: Type 2 for min-max method.

Some improvements can be seen in Fig. 16. However, the Ref. Nodes 134 gives some inaccuracy target position unlike in trilateration results, the Ref. Nodes 234 gives better accuracy by employing the min-max algorithm.

3) *Target: Type 3*

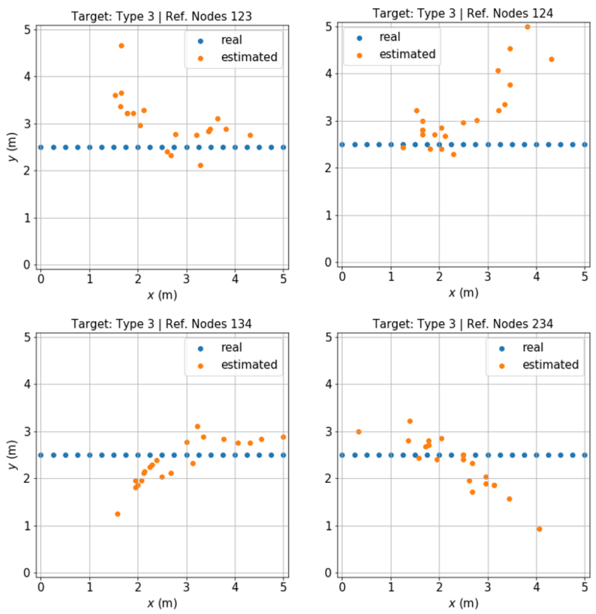

Fig. 17. Results of Target: Type 3 for min-max method.

Fig. 17 shows that in the target Type 3 there is a trend that position estimation are slightly better when the target location is in the center of the area of interest.

4) *Target: Type 4*

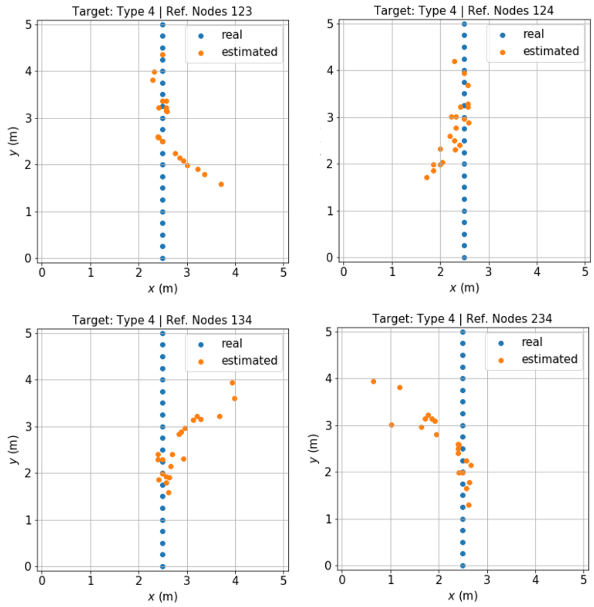

Fig. 18. Results of Target: Type 4 for min-max method.

However, in Fig. 17 and 18, we observe that the min-max algorithm gives poor performance compared to the trilateration method. Overall, the min-max gives the estimated location more accurately than the trilateration method. The RMSE of the type of the target position and type of reference nodes used are compared for both methods presented in Table 3.

TABLE III. RMSE COMPARISON

Trilateration (m)					Min-Max (m)				
Ref.	***T1***	***T2***	***T3***	***T4***	***Ref.***	***T1***	***T2***	***T3***	***T4***
123	4.3	2.7	2.1	2	123	2.7	3.2	2.1	1.9
124	3.5	3.1	2.2	2	124	3.5	2.6	2.2	1.9
134	5.3	2.7	2.4	2	134	3.6	2.5	2.1	1.9
234	2.2	2.7	1.6	1.9	234	1.9	1.9	1.9	1.9

**Ref.* represents the reference nodes and *Tn* as the target: type *n*. *n=1,2,3,4*.

VI. CONCLUSIONS AND FUTURE WORKS

We validate the proposed method by conducting the measurement campaign in the lobby indoor environment.

In this paper, we found that:

1. The trilateration and min-max are less-complex algorithms for distance-based indoor localization.
2. The area of interest of 5m-by-5m is relatively large in keeping the RSSI values reliable. The smaller area should be considered in future works.
3. The min-max has proven to have better performance compare to the trilateration. The maximum RMSE of min-max is 3.6m and trilateration is 5.3m for the same target position and reference nodes used.
4. The empirical path loss model needs to be evaluated with the shadowing effects.
5. We will consider multi-lateration for the distance-based method in our future work. The more reference nodes used need to be investigated, and the efficient placement of the reference nodes needs to be standardized.

For our future works, we will utilize other devices and other parameters i.e., link quality indicators (LQI), channel impulse response (CIR), for our indoor localization system.

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REFERENCES

[1] G. C. Bruner and A. Kumar, “Attitude toward Location-based Advertising,” *J. Interact. Advert.*, vol. 7, no. 2, pp. 3–15, 2007.

[2] R. Kulkarni, S. Dhavalikar, and S. Bangar, “Location Based Advertising System,” *Proc. - 2018 4th Int. Conf. Comput. Commun. Control Autom. ICCUBEA 2018*, pp. 1–4, 2018.

[3] J. van ’t Riet *et al.*, “Investigating the Effects of Location-Based Advertising in the Supermarket: Does Goal Congruence Trump Location Congruence?,” *J. Interact. Advert.*, vol. 16, no. 1, pp. 31–43, 2016.

[4] M. G. Wing, A. Eklund, and L. D. Kellogg, “Consumer-Grade Global Positioning System (GPS) Accuracy and Reliability,” *J. For.*, vol. 103, no. 4, pp. 169–173, 2005.

[5] S. Maddio, A. Cidronali, and G. Manes, “RSSI/DoA Based Positioning Systems for Wireless Sensor Network,” *New Approach Indoor Outdoor Localization Syst.*, 2012.

[6] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: A survey,” *Comput. Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[7] P. Pivato, L. Palopoli, and D. Petri, “Accuracy of RSS-based centroid localization algorithms in an indoor environment,” *IEEE Trans. Instrum. Meas.*, vol. 60, no. 10, pp. 3451–3460, 2011.

[8] A. Yassin *et al.*, “Recent Advances in Indoor Localization: A Survey on Theoretical Approaches and Applications,” *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 1327–1346, 2017.

[9] S. Sadowski and P. Spachos, “RSSI-Based Indoor Localization with the Internet of Things,” *IEEE Access*, vol. 6, pp. 30149–30161, 2018.

[10] S. Dolha, P. Negirla, F. Alexa, and I. Silea, “Considerations about the signal level measurement in wireless sensor networks for node position estimation,” *Sensors (Switzerland)*, vol. 19, no. 19, 2019.

[11] P. Chen, J. Shang, and F. Gu, “Learning RSSI Feature via Ranking Model for Wi-Fi Fingerprinting Localization,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1695–1705, 2019.

[12] A. T. Parameswaran, M. I. Husain, and S. Upadhyaya, “Is RSSI a reliable parameter in sensor localization algorithms - an experimental study,” *IEEE Int. Symp. Reliab. Distrib. Syst.*, pp. 1–5, 2009.

[13] X. Zhu and Y. Feng, “RSSI-based Algorithm for Indoor Localization,” *Commun. Netw.*, vol. 05, no. 02, pp. 37–42, 2013.

[14] H. Liu, H. Darabi, P. Banerjee, and J. Liu, “Survey of wireless indoor positioning techniques and systems,” *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, vol. 37, no. 6, pp. 1067–1080, 2007.

[15] J. Trogh, W. Joseph, L. Martens, and D. Plets, “An unsupervised learning technique to optimize radio maps for indoor localization,” *Sensors (Switzerland)*, vol. 19, no. 4, 2019.

[16] A. Del Corte-Valiente, J. M. Gómez-Pulido, O. Gutiérrez-Blanco, and J. L. Castillo-Sequera, “Localization Approach Based on Ray-Tracing Simulations and Fingerprinting Techniques for Indoor–Outdoor Scenarios,” *Energies*, vol. 12, no. 15, p. 2943, 2019.

[17] P. Cherntanomwong and P. Sooraksa, “Soft-clustering Technique for Fingerprint-based Localization,” vol. 30, no. 10, pp. 2221–2233, 2018.

[18] X. Luo, W. J. O’Brien, and C. L. Julien, “Comparative evaluation of Received Signal-Strength Index (RSSI) based indoor localization techniques for construction jobsites,” *Adv. Eng. Informatics*, vol. 25, no. 2, pp. 355–363, 2011.

[19] F. Zafari, A. Gkelias, and K. K. Leung, “A Survey of Indoor Localization Systems and Technologies,” *IEEE Commun. Surv. Tutorials*, vol. 21, no. 3, pp. 2568–2599, 2019.

[20] P. Cherntanomwong and D. J. Suroso, “Indoor localization system

using wireless sensor networks for stationary and moving target," *2011 8th Int. Conf. Information, Commun. Signal Process.*, no. 1, pp. 1–5, 2012.

[21] J. Y. Wang, C. P. Chen, T. S. Lin, C. L. Chuang, T. Y. Lai, and J. A. Jiang, "High-precision RSSI-based indoor localization using a transmission power adjustment strategy for wireless sensor networks," *Proc. 14th IEEE Int. Conf. High Perform. Comput. Commun. HPCC-2012 - 9th IEEE Int. Conf. Embed. Softw. Syst. ICESS-2012*, pp. 1634–1638, 2012.

[22] R. Kimoto, S. Ishida, T. Yamamoto, S. Tagashira, and A. Fukuda, "MuCHLoc: Indoor zigbee localization system utilizing inter-channel characteristics," *Sensors (Switzerland)*, vol. 19, no. 7, pp. 1–17, 2019.

[23] G. Ieee and Z. R. F. Transceiver, "Cc2420 Cc2420."

[24] W. Sakpere, M. Adeyeye-oshin, and N. B. W. Mlitwa, "A state-of-the-art survey of indoor positioning and navigation systems and technologies," *South African Comput. J.*, vol. 29, no. December, pp. 145–197, 2017.

[25] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of Wireless Indoor Positioning Techniques and Systems," *IEEE Trans. Syst. MAN, Cybern. C Appl. Rev.*, vol. 37, no. 6, pp. 1067–1080, 2007.

[26] J. J. Robles, J. S. Pola, and R. Lehnert, "Extended Min-Max algorithm for position estimation in sensor networks," *WPNC'12 - Proc. 2012 9th Work. Positioning, Navig. Commun.*, pp. 47–52, 2012.

[27] T. Chuenurajit, D. Suroso, and P. Cherntanomwong, "Implementation of RSSI-Based 3D Indoor Localization using Wireless Sensor Networks Based on ZigBee Standard," *J. Inf. Sci. Technol.*, vol. 3, no. 2, pp. 1–6, 2012.

[28] B. Rattanalert, W. Jindamaneepon, K. Sengchuai, A. Booranawong, and N. Jindapetch, "Problem investigation of min-max method for RSSI based indoor localization," *ECTI-CON 2015 - 2015 12th Int. Conf. Electr. Eng. Comput. Telecommun. Inf. Technol.*, pp. 1–5, 2015.

[29] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, "Capacity limits of MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 5, pp. 684–702, 2003.

[30] A. F. Molisch, *Wireless Communications, 2nd Edition*. John Wiley & Sons, Ltd, 2011.

[31] D. J. Suroso, P. Cherntanomwong, P. Sooraksa, and J. I. Takada, "Location fingerprint technique using Fuzzy C-Means clustering algorithm for indoor localization," *IEEE Reg. 10 Annu. Int. Conf. Proceedings/TENCON*, pp. 88–92, 2011.

[32] D. J. Suroso, P. Cherntanomwong, P. Sooraksa, and J. I. Takada, "Fingerprint-based technique for indoor localization in wireless sensor networks using Fuzzy C-Means clustering algorithm," *2011 Int. Symp. Intell. Signal Process. Commun. Syst. "The Decad. Intell. Green Signal Process. Commun. ISPACS 2011*, pp. 0–4, 2011.

[33] E. Goldoni, A. Savioli, M. Risi, and P. Gamba, "Experimental analysis of RSSI-based indoor localization with IEEE 802.15.4," *2010 Eur. Wirel. Conf. EW 2010*, pp. 71–77, 2010.

[34] M. Kim, Y. Konishi, Y. Chang, and J. I. Takada, "Large scale parameters and double-directional characterization of indoor wideband radio multipath channels at 11 GHz," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 430–441, 2014.