Measurement Arrangement for the Estimation of Path Loss Exponent in Wireless Sensor Network

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***Abstract*—Path loss model is generally used to relate distance and signal strength in wireless applications. This has been widely implemented in ranging, localization, and location tracking systems. A range of extension models have been proposed to enhance the performance for various environments and applications. Nevertheless, path loss exponent remains its significance as the main factor in the model regardless of how the model is varied. Based on the nature as an exponent of the model, inaccurate path loss exponent amplifies the error if it is used to estimate distance from received signal strength. Therefore, measurement of accurate value for path loss exponent becomes very important as it directly influences the output of distance estimation. Researchers have been studying the methods of measuring accurate path loss exponent in various environments. Instead of emphasizing the calculation process, this paper focuses more on the allocation of transmitters and receivers, and the arrangement among them. From the results obtained from experiments, properly arranged transmitter and receiver nodes provides better estimation of the path loss exponent. Based on the results, this paper also proposes a suitable nodes arrangement scheme for path loss exponent estimation.**

***Index Terms*—Location estimation, path loss model, radio propagation, ranging, received signal strength.**

I. INTRODUCTION

Under the new trend of ubiquitous research, localization [1] becomes one of the inevitable functions designed together with other core functions such as security, routing/networking, scheduling, and information processing. In the future, widely spread wireless sensor network (WSN) is able to cover both indoor and outdoor environment. Since distance ranging is the foundation for localization, it becomes an on-going research toward more possible and reasonable implementation in various location based applications.

Among the distance ranging techniques, radio ranging is widely accepted to be used in WSN. Radio ranging can be achieved through the measurement of physical change encountered during signal propagation [2, 3]. Using received signal strength indicator (RSSI) measured at receiver, distance estimation between transmitter and receiver can be very easy and convenient. Nowadays, RSSI ranging is mainly adopted among short range wireless communication systems because RSSI measurement is done in every RF transceiver. Therefore, no additional components and power consumption are necessary.

Considering current existing technology, there is a tradeoff between ranging accuracy and other implementation-related factors such as low power consumption, small size device, ease of implementation, and minimum number of electronic components to be integrated. If ranging accuracy is required, we need to sacrifice other benefits. For example, high performance sensors are inevitable for each sensor node. This indeed increases the overall implementation cost. In addition, the additional expensive components are generally high power consumption and large in size such as ultrasonic transducers.

A more reasonable approach uses existing components for ranging and location estimation such as wireless communication module. The wireless communication module is vital to almost all of the devices and machines. It does not just provide digital communication ability but also attached with received signal strength measurement. Thus, we can use RSSI to estimate distances among nodes and location coordinate for all devices [3]. Using RSSI available in the existing wireless communication modules, implementation of location system can be very easy, cheap in cost, low in power consumption, and small in size.

Radio ranging using RSSI provides competitive advantages but further research is necessary for its sensitive reaction due to environment. RSSI ranging can be inaccurate and inconsistent especially in indoor environment [4]. Radio signal propagation could be reflected and attenuated by wall materials. Multipath propagation happens more frequently and more seriously in an enclosed small room. Environmental changes such as temperature / humidity, human activities, and objects arrangement cause parameters deviation. All these problems are combined and lead to difficulty in accurate radio ranging requirement.

Radio ranging using RSSI generally considers three models: [5] small scale (spatial and temporal) multipath fading, [6] medium scale (spatial) shadowing model, and [7] large scale (spatial) path loss (PL) model as shown in Fig. 1 [8].

Among them, multipath fading effect is unwanted and can be mitigated by filters. Shadowing model explains the slow signal-strength fluctuation versus distance. This effect is caused by multipath signal propagation encounters reflection(s) and diffraction. Many researchers attempt to eliminate this effect but the harvest is not significant. This effect can be emulated by ray tracing methods [9]. The last model, path loss model is an empirical model which describes the attenuation of signal strength versus distance. Path loss model is the only model that contributes to RSSI radio ranging.

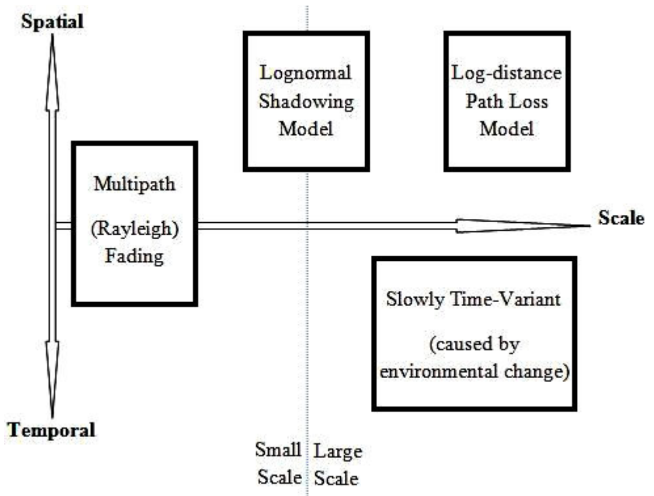

Fig. 1. RSSI variation and the models

To improve the accuracy of RSSI ranging, several ways can be considered. From the block diagram shown in Fig. 2, it is possible to identify the components that allow enhancement.

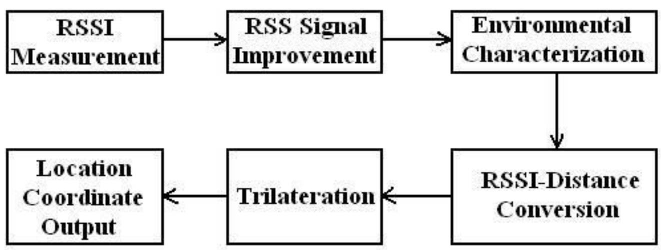

Fig. 2. RSSI-to-distance block diagram

In Fig. 2, RSS signal improvement is mainly to filter noise and fast fading effect [10]. This increases the stability of the RSSI signal. Both RSSI-distance conversion and trilateration (or multi-lateration) can be enhanced in algorithm level [11]. Environmental characterization provides measurement for path loss exponent. If the calibrated path loss exponent is accurate enough, the result obtained from RSSI-distance conversion becomes accurate [12, 13].

The measurement of path loss exponent can be inaccurate and uncertain when direct wave (line of sight, LOS) is weak while reflected waves are strong. The objective of this study is to find accurate path loss exponent under low propagation attenuation environment such as indoor places. Instead of investigating the calculation and processing of the RSSI for path loss exponent, we focus on the arrangement of sensor nodes including the locations of transmitters and receivers.

II. Related Works

Radio propagation and path loss models are well defined research topic with firm theoretical background [14]. It leads to the development many location related applications. Especially in today's mobile computing world, localization obtains its implementation in more practical ways for our daily life. This produces more researches on practical implementation recently. From the algorithm aspect, [15] proposed three methods for large scale WSN. The first method uses mean interference, the second method is based on virtual outage probabilities, and the third one applies cardinality of the transmitting set. The experiments were based on a generic system model for simulation.

The estimation of path loss exponent relies on the measurements of the received signal strength together with the corresponding locations. However, accurate measurement of locations and distances could be difficult in some environments. Therefore, [13] proposed a continuous calibration scheme based on the Cayley-menger determinant. This method avoids distance measurement while performing path loss estimation in WSN. The main contribution which replaces location and distance measurement is using geometric constraints and the planarity of sensor networks. This paper induced other online calibration algorithms developed for path loss exponent estimation.

In many WSN applications, the localization requirements can be achieved in building or at fixed locations. When it is applied to mobile nodes, the estimation of the path loss estimation does not just depend on online-calibration techniques, but also Doppler Effect. [16] proposed a dynamic estimation method for path loss exponent measurement using both Doppler effect and RSSI. The strong point of this research is that the method is good in vehicular environment. This is good for distance estimation between vehicles.

Almost all researches are algorithm oriented for wireless ranging. A relatively less number of research activities mentioned about the acquisition of practical samples. For a practical research done in [17], data collection and the procedures were stated clearly. In this study, the acquisition of signal strength values was done in two ways: track run measurement and single marker measurement. By knowing the pre-designed path and location spot, the estimation of the path loss exponent can be achieved with the pair values of RSSI and location coordinate.

III. Path Loss Model and Ranging

Path loss model was developed to estimate or predict the possible received signal strength on receiver. It was first used in determining the coverage of radio signal in a specific region given the optimized antenna location and height. It becomes useful for distance and location finding when mobile applications and ubiquitous computing are widely deployed.

In most radio transceiver modules, the measurement of received power is just an auxiliary function. The measured value provided by the module may not be exactly received power in dBm. However, received signal strength indicator (RSSI) is used to represent the condition of received power level. This can be easily converted to a received power by applying offset to obtain the correct level:

$$P_i = \left(RSSI_i + RSSI_{\text{offset}}\right) \tag{1}$$

where P_i is the actual received power from transmitter node i. $RSSI_i$ is the measured RSSI value for transmitter node i, which is stored in the RSSI register of the radio transceiver. $RSSI_{\text{offset}}$ is the offset found empirically from the front end gain and it is approximately equal to -45 dBm. This is to make sure that the actual received power value has dynamic range from -100 to 0 dBm, where -100 dBm indicates the minimum power that can receive, and 0 dBm indicates the maximum received power.

If RSSI ranging is used to measure the distances between transmitter and receiver, log-distance path loss model [18] is used to express the relationship between received power and the corresponding distance as shown in the following expression:

$$P_r(d) = P_r(d_0) - 10 \times n \times \log_{10}\left(\frac{d}{d_0}\right) \tag{2}$$

where $P_r(d)$ is the received power of the receiver measured at a distance d to the transmitter, which is expressed in dBm.

In path loss model, two important parameters are used to characterize environment: path loss exponent n and the received power $P_r(d_0)$. $P_r(d_0)$ is the measured received power at distance d_0 to the transmitter. To characterize the environment for RSSI ranging, received power $P_r(d_0)$ is first measured by allocating a receiver d_0 apart from the transmitter. d_0 is generally fixed at 1 meter. After $P_r(d_0)$ is obtained, the receiver is moved to other locations randomly to measure the received power with the corresponding distance.

IV. Path Loss Exponent Estimation

In this paper, we investigated two types of method for path loss exponent estimation. One method is to calculate the path loss exponent using a number of received powers and the corresponding distances. This method is called one-line measurement as the collection of RSSI values was done by locating the transmitter and receiver along a straight line, and varying the distance between them.

Another method is to directly update the environmental parameters using gradient decent technique. In this case, measurement of received power can be done in spread and random style as long as the exact locations in the area are known. This method is called online-update measurement as the environmental parameters such as path loss exponent can be updated continuously regardless of the change of environment.

For one-line measurement, received powers must be collected along the line with distance marked on the line. The collected RSSI values represent the received power at each marked distance along the line including the one-meter-place received power $P_r(d_0)$. When field measurement is done, the received powers (in dBm) are plotted in a graph versus distance. A straight line can be drawn along the received powers $P_r(d)$ when the distance is using logarithmic scale:

$$D = 10 \times \log_{10}\left(\frac{d}{d_0}\right) \tag{3}$$

To find path loss exponent n, the gradient of the straight line is used:

$$n = \frac{Pr(d_{\min}) - Pr(d_{\max})}{10 \times \left\{\log_{10}\left(\frac{d_{\max}}{d_0}\right) - \log_{10}\left(\frac{d_{\min}}{d_0}\right)\right\}} \tag{4}$$

Theoretically, every room/area has only one set of environmental parameters. However, the fact is that every location also has their own value although two locations are in the same area and they are neighbor. This can be verified when the measurement line is moved or rotated toward another direction, the estimation result will be slightly different. Note that a small change in path loss exponent n leads to drastic change in distance estimation.

The reason of this problem is the RSSI location-dependent variation especially in the medium scale spatial domain variation. Suppose we use uncertain and location-varied RSSI source for calculation, it is impossible that we are able to obtain accurate environmental parameters from inaccurate source. This causes different environmental parameters obtained at different locations. This indeed increases the difficulty of measuring accurate value of path loss exponent.

For online-update measurement, the measurement coordinates (x,y) must be predetermined. Three or four transmitters are required to be located in the area with coordinates (x_1,y_1), (x_2,y_2) and (x_3,y_3). If the distances d_1, d_2, and d_3 between transmitters and receiver can be found using path loss model, the estimated location coordinate can be calculated using lateration:

$$\begin{aligned} {d_1}^2 &= (x_1 - x)^2 + (y_1 - y)^2 \\ {d_2}^2 &= (x_2 - x)^2 + (y_2 - y)^2 \\ {d_3}^2 &= (x_3 - x)^2 + (y_3 - y)^2 \end{aligned} \tag{5}$$

By comparing the actual location coordinate with the estimated coordinate, the error between them can be found. However, it is highly unstable if we want to use the error to adjust the environmental parameters using gradient decent technique.

A more stable way is to find the calculated received power from predetermined location coordinates using both lateration and path loss RSSI-to-distance conversion. By comparing the calculated received power $P_r(d)$ with the measured received power $P_r'(d')$, the error between them can be found and used in gradient decent adjustment:

$$e = P_r(d) - P_r'(d') \tag{6}$$

To adjust path loss exponent n, the gradient vector is found using the mean-square error of the received powers:

$$\nabla_n E\left(e^2\right) = 2\left[P_r(d) - P_r'(d')\right]\left(10\log_{10}\frac{d}{d_0}\right) \tag{7}$$

To adjust received power $P_r(d_0)$, the gradient vector is found using the mean-square error of the received powers:

$$\nabla_{Pr} E\left(e^2\right) = -2\left[P_r(d) - P_r'(d')\right] \tag{8}$$

Recursive expressions can be used to update the parameters using the gradient vectors in (7) and (8):

$$n_{(k+1)} = n_{(k)} + \frac{1}{2}\mu\nabla_n E\left(e^2\right) \tag{9}$$

$$P_{r(k+1)}\left(d_0\right) = P_{r(k)}\left(d_0\right) + \frac{1}{2}\mu\nabla_{Pr} E\left(e^2\right) \tag{10}$$

where μ is the step size of the parameters. It controls the speed and stability of the convergence.

This method provides global measurement for the environmental parameters as compared to one-line measurement. This is because the measurement involves 3 or 4 transmitters located at each corner of the measurement area. Therefore, the estimation result is valid for all locations within the whole area.

V. Data Collection Arrangement

In [17], two approaches of data collection were adopted: track run measurement and single marker measurement. Although single marker measurement is done with selected locations without following a line, these approaches still remain at the ranging aspect. From localization aspect, the measurement should be done with all transmitters involved within the active area.

In this paper, we would like to propose a measurement arrangement so that the collected RSSI values provide global and accurate estimation for path loss exponent. In this case, it should implement online-update measurement approach for global validity. However, the online-update measurement still cannot provide optimized performance as different locations still can provide different accuracy.

Our proposed measurement arrangement tries to minimize the location error caused by location-dependent parameters. To achieve this objective, our proposed approach becomes greatly different from the ordinary arrangement. In our proposal, instead of changing the location of the receiver, it becomes stationary in our scenario. This means we have to change the location of the transmitters. The reason of keeping receiver stationary and changing the location of the transmitter is to create a condition so that the receiver always remains at the center of the transmitters. To avoid complexity, we simplify the localization by shaping the area to rectangle formed by four transmitters as shown in Fig. 3.

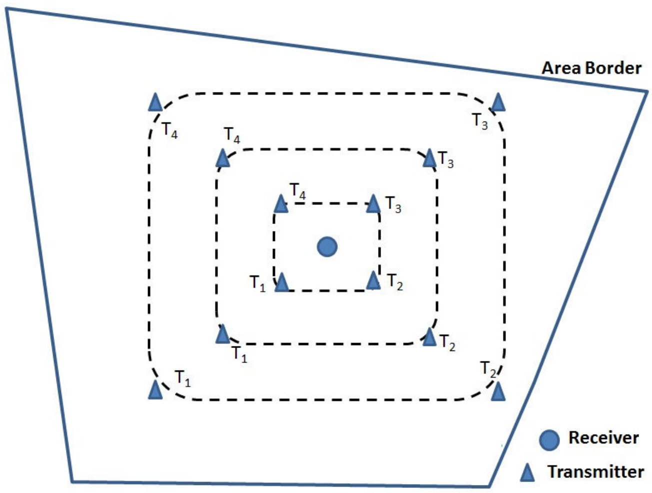

Fig. 3. Rectangular shaping

In Fig. 3, the measurement area can be in any shape. However, the allocation of the four transmitters always forms a rectangular shape to include the receiver at the center of the rectangle. The shape formed by the transmitters can be either from-small-to-big or from-big-to-small when the measurement samples are collected. This could also lead to different estimation accuracy as discussed in the following sections.

Using rectangular shape, the calculation can be simplified. For the expression in (5), it becomes

$$d_1 = d_2 = d_3 = \frac{R}{\sqrt{2}} \tag{11}$$

where R is the length or width of the rectangle.

VI. Results and Discussions

To perform the experiments for our proposed method, we prepared an empty outdoor space (10 m × 10 m) without obstacles in the area, and with minimum side buildings. The nearest tree is at 12 meter away from the border of our experiment area. This is to avoid the influences to our results if it is applied to different environments. We also reduced the interference of human activities by using wireless remote triggered sensor nodes while performing the field measurement tasks.

In our experiment, we decided to perform both one-line measurement and online-update measurement. Under the category of online-update measurement, we performed three sub-tasks:

Sub-task 1: Predesigned spread locations measurement.
Sub-task 2: From-small-to-big rectangular measurement.
Sub-task 3: From-big-to-small rectangular measurement.

To perform one-line measurement, we marked a straight line along the center of the area. The measurement started with a distance of 100 cm from transmitter to receiver until 900 cm away from transmitter. Between the two ends, measurement was done in every 50 cm. Therefore, it provides a total of 17 readings. The values were plotted in a graph as shown in Fig. 4.

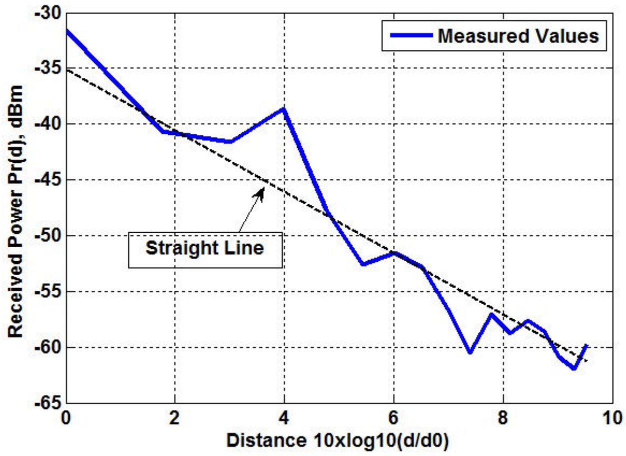

Fig. 4. One-line measurement

In Fig. 4, $P_r(d_0)$ was measured at many locations by moving both transmitter and receiver together for all locations and directions with 100 cm apart. The average value was found to be −35 dBm. Therefore, we can draw a straight line in Fig. 4 to find the gradient of the line. Based on the line, the difference between maximum and minimum received power is (−35 dBm + 62 dBm = 27 dB). The difference between the maximum and minimum distance is [$10\log_{10}(900/100) - 10\log_{10}(100/100) = 9.5424$]. By applying (4), we can find $n = (27/9.5424) = 2.83$.

To perform sub-task 1 for predesigned spread locations using online-update method, we randomly selected 11 locations. These locations are evenly distributed in the (10 m × 10 m) area as shown in TABLE I.

TABLE I. PREDETERMINED LOCATION FOR SUB-TASK 1

(*x* cm, *y* cm)	(*x* cm, *y* cm)
(50,50)	(200,600)
(250,400)	(350,850)
(300,200)	(650,800)
(600,200)	(950,900)
(750,400)	(800,600)
(900,300)	

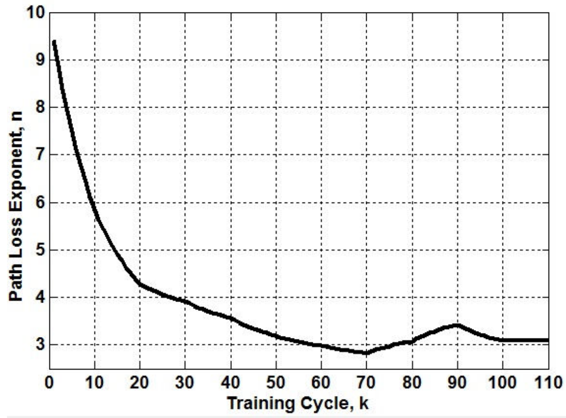

Fig. 5. Sub-task 1: Calibration of *n*

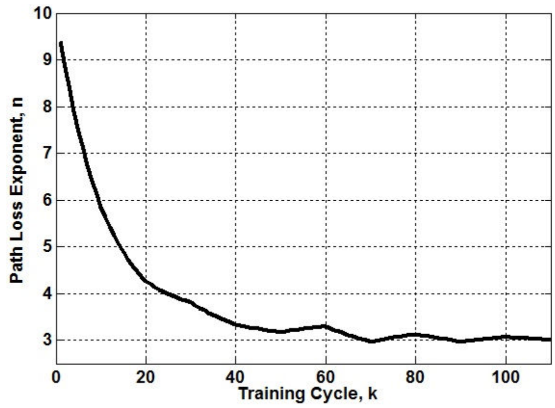

Fig. 6. Sub-task 2: Calibration of *n*

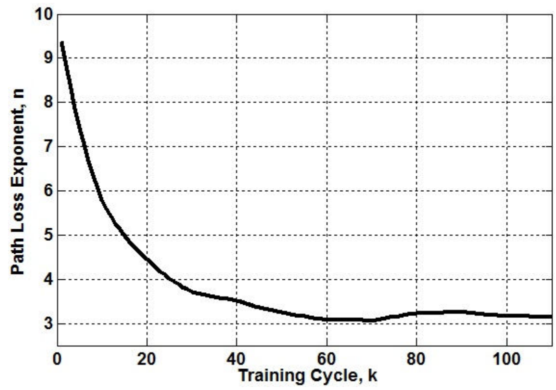

Fig. 7. Sub-task 3: Calibration of *n*

The four transmitter were located at each corner of the area (0,0), (1000,0), (0,1000), and (1000,1000). These coordinates are stated in centimeter. The expression in (9) is used to update the parameter n. Step size μ was given as 0.01. For each measurement location, 10 training cycles were included. Therefore, a total of 110 training cycles was used for calibration. For each cycle, the value of path loss exponent n was recorded as shown in Fig. 5.

To perform sub-task 2 and 3, the receiver was located at the center of the area (500,500). The four transmitters were assigned at each corner of the rectangles. The size of the rectangles range from (200 cm × 200 cm), (300 cm × 300 cm), (400 cm × 400 cm), … until (1200 cm × 1200 cm). Again, each size was given 10 training cycles. Therefore, a total of 110 training cycles was used for calibration. Step size μ was given as 0.01. For each cycle, the value of path loss exponent n was recorded as shown in Fig. 6 and 7. Fig. 6 was obtained from sub-task 2 and Fig. 7 was obtained from sub-task 3.

To evaluate the performance among the three sub-tasks, three criteria were used: speed of convergence, stability, and convergence accuracy. By comparing Fig. 5, 6, and 7, it is clear that all sub-tasks provide similar convergence speed. This is because the step size μ is common. For stability, sub-task 2 and 3 presents better stability as compared to sub-task 1. For convergence accuracy, we implemented the final calibrated n into location estimation. The final calibrated n obtained from sub-task 1, 2, and 3 are 3.05, 3.00, and 3.10 respectively. The movement path of the location estimation is from (0, 500) to (1000,500). The estimated results were shown in Fig. 8. From observation, the result obtained from sub-task 3 is more accurate as compared to subtask 1 and 2. This shows that the convergence accuracy from sub-task 3 is better.

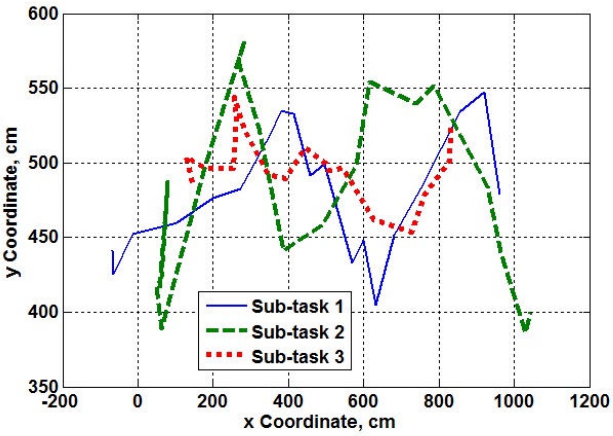

Fig. 8. Location estimation using the three converged n

VII. Conclusions

Our research has shown that measurement arrangement can provide better path loss exponent estimation. From Fig. 4, we can see that the estimated n = 2.83 is far different from the accurate estimation from sub-task 3 (n = 3.10). Using our proposed rectangular measurement, the estimation accuracy can be further improved as compared to other online-update approaches.

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