Indoor Localization for Multi-Wall, Multi-Floor Environments in Wireless Sensor Networks

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***Abstract*—In recent years, importance of indoor localization has increased in Wireless Sensor Networks (WSNs). Extremely complex nature of the indoor environments makes WSN research more difficult than in the outdoor counterparts. In WSNs, the Received Signal Strength (RSS) from sensors is usually utilized to locate unknown sensors or nodes. However, the RSS is relatively sensitive to indoor obstructions such as walls and ceilings between adjacent floors. Various indoor localization algorithms are available, but most are not suitable because of the complex indoor environments. This paper proposes a novel localization scheme which uses vertical allocation of beacon sensors to estimate floor attenuation and wall attenuation. These two parameters are then used to identify the floor number and to estimate the horizontal localization of an unknown node, respectively. Simulation results show that both schemes provide accurate localization performance.**

Keywords—Wireless sensor network; Indoor localization; Multi-floor; Multi-wall; Attenuation; Received signal strength

I. INTRODUCTION

With the development of wireless networks and digital communication devices, people are paying increasing attention to location-based services. These can be applied in many fields such as vehicle systems, tourist guides, and personal security, to name a few. The Global Positioning System (GPS) is a mature and widely used technique, especially in outdoor positioning or localization, due to its high accuracy [1]. Unfortunately, GPS is not suitable for large-scale sensor networks because of its high hardware costs and energy requirements. More importantly, GPS is not suitable for use indoors because of its low penetrating satellite signals. Hence, indoor localization technology is more challenging, and it has become an important focus of research interest in recent years [2].

The availability of Wireless Sensor Networks (WSNs) has contributed to indoor localization [3]. In general, a WSN is composed of numerous low-power sensors or nodes, which are designed to be a small computing unit. A WSN is usually equipped with different kinds of sensors to monitor targets and communicate with each other. Due to its small size and low-cost nature, a large number of sensors can be easily used to locate the target in a building. The localization method proposed in this paper is suitable for indoor environments with WSN with multiple floors and multiple walls.

The remainder of this paper is organized as follows. Section II discusses previous work in localization for WSN. Section III describes the system model including the estimation of the attenuation of the floors and the walls. In Section IV, we propose a localization scheme which utilizes the estimated attenuation values from the previous section to identify the floor number and the localization of the plane. Section V presents an improved approach to increase the localization accuracy. The simulation results are given in Section VI, followed by the concluding remarks in Section VII.

II. RELATED WORKS

A variety of localization methods for WSNs have been proposed. In relation to the locations of nodes, those for which the coordinates are known in advance are called beacon nodes. If the location is not known in advance, they are called unknown or target nodes. Existing localization algorithms are largely divided into two typical categories depending on the distance between beacon node and unknown node: range-based [4] and range-free [5]. The former is defined by protocols that use absolute point-to-point distance (or range) estimates or angle estimates for estimating the location. The latter uses network connectivity and other information to localize the nodes. There are some typical algorithms such as the centroid algorithm, Approximate Point in Triangle Test (APIT), DV-hop and so on. However, a large number of nodes are required for effective range-free localization.

In range-based schemes, Received Signal Strength (RSS) based localization is less expensive and simple to implement in hardware. Thus, it is widely used as compared to other methods such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA) schemes. However, the RSS scheme is very sensitive to fading effects and multipath reflection. Numerous methods are proposed to solve this problem, although their effects are not satisfactory. Generally, a

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proper propagation model suitable for complex indoor environment is significant and some models are also proposed. The Multi-Wall (MW) model proposed in [6] only considers attenuation caused by wall number and its texture. However, the number of walls should be known in advance and the floor attenuation in multi floor building is not also considered. These indoor obstructions such as walls, material layers will result in low localization accuracy. To address the issue caused by obstruction, this paper designs a sensor-based localization scheme in which the sensors are aligned vertically. This scheme takes the floor and wall attenuation into consideration. Also, it is mainly analyzed by using a simple application example.

III. System Model

A. Allocation of Beacon Nodes

With respect to the allocation of the beacon nodes, each floor is supposed to be equipped with the same number of nodes which have the same horizontal coordinates. Thus, each beacon node and its adjacent beacon node upstairs and downstairs comprise a vertical group. This group is used to estimate the floor attenuation and the wall attenuation in the following scheme. Fig.1 shows this type of allocation of the beacon nodes. In this paper, four vertical groups are set at the corner of the plane area and H is the distance between adjacent beacon nodes in the same vertical group.

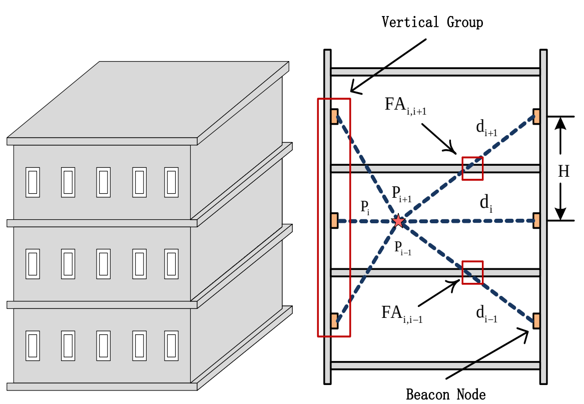


Figure 1. Allocation of vertical beacon nodes

B. Floor Attenuation Estimation

The floor attenuation is estimated as shown in Fig. 1 where $FA_{i,i+1}$ denotes the floor attenuation between the i-th floor and the $i+1$-th floor. Based on a conventional RSS model [7] as given in (1), a new RSS model for floor attenuation estimation is proposed by (2).

$$PL(d) = PL(d_0) + 10\mu \log_{10}(d/d_0) + X_s \qquad (1)$$

$$PL(d) = PL(d_0) + 10\mu \log_{10}(d/d_0) + FA + X_s \qquad (2)$$

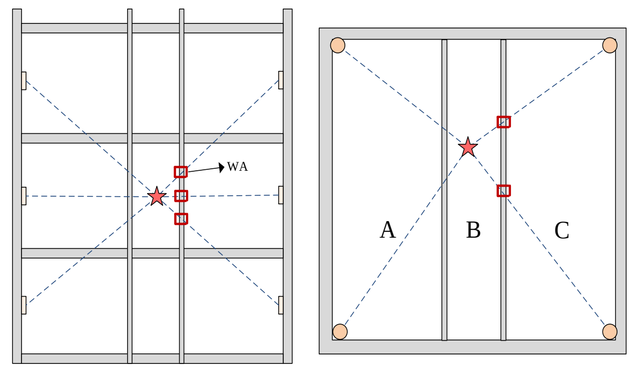
where d is the distance between the transmitter and the receiver, d_0 is the reference distance, μ is the path loss exponent, FA is the floor attenuation, and X_s is a zero-mean normally distributed random variable.

C. Wall Attenuation Estimation

Based on the floor attenuation model, we consider a wall attenuation during propagation as shown in (3).

$$PL(d) = PL(d_0) + 10\mu \log_{10}(d/d_0) + FA + nWA + X_s \qquad (3)$$

where n is the number of walls during the propagation and WA is the single wall attenuation. Note that WA needs to be measured in advance. Here, as a simple illustrative case shown in Fig.2 (b), two vertical walls that divide the horizontal plane into three areas are set in the building.



(a) (b)

Figure 2. Wall attenuation estimation model and plane positioning

Actually, this wall attenuation model proposed here is suitable for the buildings with the same room layout in each layer. That will guarantee that the signals will suffer from the same wall attenuation from the same vertical group between adjacent layers.

IV. Proposed Localization Scheme

A. Floor Number Identification

For a vertical group, we can transform the measured RSS attenuations from the middle beacon node PL_i, the upstairs beacon node PL_{i+1}, or the downstairs beacon node PL_{i-1} to the distance using (1) and (2), respectively. Then, (4) and (5) can be obtained. According to the geometry theory, the following relationship (6) can be also derived.

$$d_i = 10^{\frac{PL_i - PL(d_0)}{10u}} \qquad (4)$$

$$d_{i+1/i-1} = 10^{\frac{PL_{i+1}/PL_{i-1} - FA_{i+1}/FA_{i-1} - PL(d_0)}{10u}} \qquad (5)$$

$$H^2 + d_i^{\,2} = d_{i+1}^{\,2} = d_{i-1}^{\,2} \qquad (6)$$

Then, by inserting (4) and (5) into (6), the floor attenuation between the i-th floor and the $i+1$-th floor

$FA_{i,i+1}$ or $FA_{i,i-1}$ between i -th floor and i-1 -th floor can be calculated by (7).

$$FA_{i,i+1/i-1} = P_{i+1/i-1} - PL(d_0) - 5u\log_{10}(H^2 + 10^{\frac{PL_i - PL(d_0)}{5\mu}}) \tag{7}$$

If the floor attenuation for each floor is obtained through *a priori* experimental measurement, the estimated floor attenuation with (7) can be employed, together with Minimum Euclidean Distance Matching (MEDM) as shown in (8) to identify the location of the floor of the unknown node. $PFA_{i,i+1}$ is the priori floor attenuation between the i -th floor and i+1 -th floor. For instance, the estimated i -th floor attenuation value is shown in the last column of Table 1. After the matching process with the second floor attenuation and the fourth floor attenuation, respectively, the estimated floor of the unknown node is equal to 4, depending on the minimal matching value shown in Table 1.

$$MEDM = \sqrt{(FA_{i,i-1} - PFA_{i,i-1})^2 + (FA_{i,i+1} - PFA_{i,i+1})^2} \tag{8}$$

TABLE 1. FLOOR NUMBER IDENTIFICATION USING ESTIMATED ATTENUATION VALUES

Estimated value	Floor number		
	2	4	i
$\boldsymbol{FA_{i,i-1}}$	$PFA_{2,1} = 15.4\ dB$	$PFA_{4,3} = 18.7dB$	$FA_{i,i-1} = 17.9dB$
$\boldsymbol{FA_{i,i+1}}$	$PFA_{2,3} = 18.7dB$	$PFA_{4,5} = 16.9dB$	$FA_{i,i+1} = 17.3dB$
MEDM	2.87	0.89	$i = 4$

This floor identification approach can achieve a high accuracy, especially where there is a large difference in the floor attenuation between the different floors. In practical terms, it can be applied in buildings with significant floor structure differences.

B. *Plane Positioning*

Due to similar structural composition and distribution of the walls in each floor of the building, the signal is likely to suffer from the same wall attenuation from the same vertical group between two adjacent floors. Let WA_j be the wall attenuation during the propagation from the j -th vertical group. According to the geometry theory used in floor number identification, we have

$$d_i = 10^{\frac{PL_i - PL(d_0) - WA_j}{10u}} \tag{9}$$

$$d_{i+1/i-1} = 10^{\frac{PL_{i+1}/PL_{i-1} - FA_{i+1}/FA_{i-1} - WA_j - PL(d_0)}{10u}} \tag{10}$$

$$WA_j = -5u\log_{10}\left(\frac{H^2}{10^{(\frac{PL_{i+1/i-1,\ j} - FA_{i,i+1/i-1} + PL(d_0)}{5\mu})} - 10^{(\frac{PL_{i,j} - PL(d_0)}{5\mu})}}\right) \tag{11}$$

where $PL_{i,j}$ is the measured RSS attenuation from the i -th floor's beacon node of the j -th vertical group.

After the wall attenuation from each beacon node has been estimated using (11), the location of the unknown node can be evaluated. However, *a priori* information on the distribution of the walls should be obtained in advance as shown in Fig. 2(b). For convenience, a wall number matrix, $WN^{N\times M}$ is defined as shown in (12).

$$\begin{bmatrix} 0 & 2 & 0 & 2 \\ 1 & 1 & 1 & 1 \\ 2 & 0 & 2 & 0 \end{bmatrix} \tag{12}$$

where N is the number of areas and M is the number of beacon nodes for each layer. Actually, M is also the number of vertical groups in every three layers.

The estimated wall attenuation can be transformed into the estimated wall number by utilizing the measured WA in (3). Based on that, we can know whether there exists walls and how many walls along each propagation path. Then, we can match the estimated wall number with each row of the prior wall number matrix $WN^{N\times M}$ one by one using the MEDM. In that case, the area of the unknown node will be accurately determined.

To achieve a high localization accuracy, the wall attenuation of each floor where the unknown node is located should be eliminated. Here, we use two methods to revise the measured RSS of the unknown node. One involves direct utilization of the estimated wall attenuation, and the other entails using WA and the estimated wall number.

After we revise the RSS, the conventional plane algorithm can be applied to the plane localization. For the triangle method given in [8], the RSS of at least three beacon nodes should be selected. Using the conventional RSS model, we can transform the RSS into the distance and put it into the plane localization. Here, we denote (x, y), (x_1, y_1), (x_2, y_2), (x_3, y_3) as the locations of the unknown node and the three selected beacon nodes. Then, for the selected three beacon nodes on the horizontal planes, we denote $d_{i,1}$, $d_{i,2}$, and $d_{i,3}$ as the distances between the unknown and the three selected beacon nodes on the i -th floor. Using (13) and (14), the estimated coordinates of the unknown node can be obtained as

$$\begin{aligned} \alpha &= (d_{i,1}{}^2 \text{-} d_{i,2}{}^2) - (x_1{}^2 - x_2{}^2) - (y_1{}^2 - y_2{}^2) \\ \beta &= (d_{i,1}{}^2 \text{-} d_{i,3}{}^2) - (x_1{}^2 - x_3{}^2) - (y_1{}^2 - y_3{}^2) \end{aligned} \tag{13}$$

$$x = \frac{\begin{vmatrix} \alpha & 2Y_1^2 \\ \beta & 2Y_1^3 \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 \\ 2X_1^3 & 2Y_1^3 \end{vmatrix}} \quad y = \frac{\begin{vmatrix} 2X_1^2 & \alpha \\ 2X_1^3 & \beta \end{vmatrix}}{\begin{vmatrix} 2X_1^2 & 2Y_1^2 \\ 2X_1^3 & 2Y_1^3 \end{vmatrix}} \tag{14}$$

where X_b^a and Y_b^a refer to $(x_a - x_b)$ and $(y_a - y_b)$.

In fact, the location of the unknown node can be obtained with $\binom{M}{3}$ selections of the RSSs. However, preference should be given to an RSS that experiences less wall attenuation or even no attenuation. Although we have revised the RSS by eliminating the wall attenuation, error always exists between the real wall attenuation and the estimated wall attenuation. Here, we can select the beacons depending on the smallest three wall number values for the corresponding row of $WN^{N\times M}$. In a best-case scenario, there are three RSSs without wall attenuation. That is to say, there should be at least three zeros for some rows of $WN^{N\times M}$ in that case.

V. IMPROVED LOCALIZATION METHOD

The method given in Section III uses three distances from three beacon nodes to the unknown node to determine three circles. Based on the geometry theory, the point at which three circles intersect represents the coordinates of the unknown node. However, using three revised RSSs will still cause inevitable errors because we cannot completely eliminate the wall attenuation. Thus, we only utilize the RSSs from two beacon nodes to determine the position of the unknown node. The RSS from the third beacon node is not considered or it is only used as reference information. The analysis of the location of the two circles yielded five cases, as shown in Fig. 3.

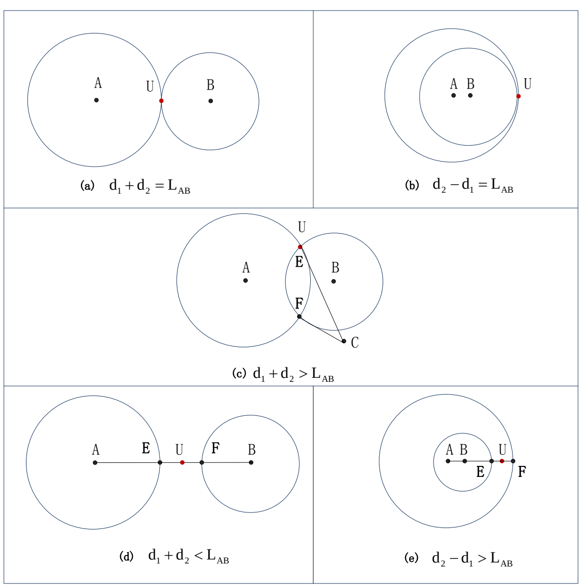


Figure 3. Five cases of using two circles to determine the location of the unknown node

When the two circles are externally tangent or internally tangent as shown in Figs. 3(a) and (b), the estimated intersection point of the unknown node is taken.

If the two circles intersect, there are two intersection points as shown in Fig. 3(c). In this case, we use a revised RSS between the third beacon node and the unknown node as the reference to compare $|d_3 - CE|$ with $|d_3 - CF|$ and select the smaller one as the estimated unknown node. Here, RSS from the third beacon node is utilized as a reference to identify the proper position between two intersection points.

In addition, as shown in Figs. 3(d) and (e), there may be no intersection point because of measurement error. In these cases, we take the middle point of E and F as the unknown node.

With respect to this improved method, we use the RSSs of two beacon nodes instead of three to decrease the error caused by the wall attenuation. However, the best case is when two RSSs without any wall attenuation are available, or that there are two zeros in some rows of the wall number matrix.

VI. SIMULATION RESULTS

In this section, the performances of the proposed localization and attenuation methods along with the improved method are demonstrated through computer simulation in MATLAB. As shown in Fig. 2, four beacon nodes are allocated in each floor whose area is 10 m×10 m, and the device in any position of this area is assumed to be able to detect all the beacon nodes. As there are two parallel walls, each horizontal plane is divided into three small areas *A*, *B*, and *C*. The corresponding wall number is shown in each row of the matrix given in (12). Here, both the estimated attenuation-based and prior attenuation-based revisions are applied to each area. Additional parameters are as follows: $PL(d_0)$ was set to 20 dB because free space propagation environment is assumed, and μ is set to be 2.0. The single wall attenuation and the floor attenuation were 20 dB and 30 dB, respectively. Here, Root Mean Square Error (RMSE) is defined in (15) to evaluate the localization performance.

$$RMSE = \sqrt{(x_{est} - x_{real})^2 + (y_{est} - y_{real})^2} \qquad (15)$$

where (x_{est}, y_{est}) and (x_{real}, y_{real}) are estimated coordinate and actual coordinate, respectively.

The effect of different noise variances on the localization performance for each area using two methods is simulated in Fig. 4. Through the simulation results, we observe that the accuracy of area A and C are nearly the same because these two areas suffer from similar wall attenuation. In addition, area B achieves the best localization performance. There is no gap between the wall attenuation from the beacon nodes. Thus, there is a similar error from each beacon node. When we use (13) and (14) to locate the unknown node in area B , some parts of that same error will be eliminated automatically, thereby further increasing the localization accuracy.

On the other hand, if we use prior wall attenuation to revise the RSS, the same performance can be obtained, irrespective of the location of the unknown node. As prior attenuation approaches focused mainly on actual attenuation, the revised RSS will be extremely close to the RSS without any walls. Thus, the presence of the walls does not give rise to any errors. However, there is always a gap between the prior attenuation and the actual attenuation. In worse cases, the prior information is not available. Thus, in most cases, we can only make use of the estimated attenuation to locate the target node.

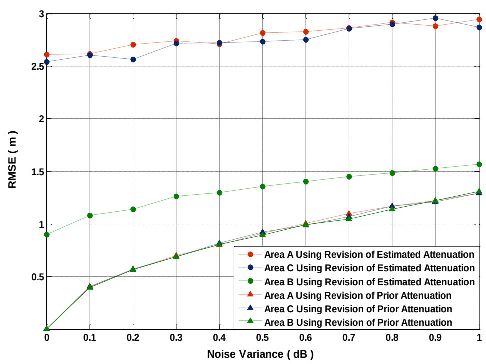


Figure 4. Localization performance in each area using two revision methods

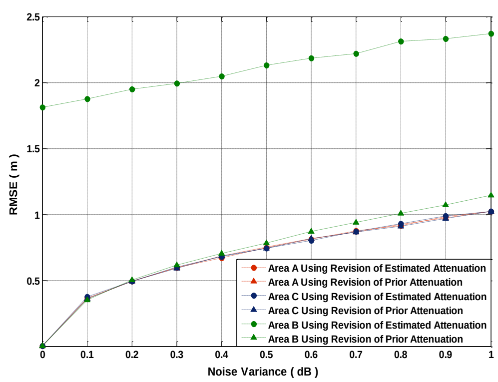


Figure 5. Localization performance in each area using two revision methods for improved algorithm

With respect to the improved method, using the same parameters as the previous method, we obtained the simulation performance in each area with two revision methods, as shown in Fig. 5. Obviously, the accuracy is increased, especially for areas *A* and *C* . However, we obtained a slightly worse performance in area *B* compared to the previous method. Some errors eliminated in area *B* in the previous method were not eliminated in this improved method. Hence, the previous method is the optimal choice for areas that suffer from the same wall attenuation from the beacon nodes. To this end, additional exploration is needed to determine the optimal choice between the two approaches used in this paper according to the detailed attenuation situation of the unknown node. And the performance is also influenced by *FA* and

VII. CONCLUSION

In this paper, we proposed a floor-wall attenuation estimation scheme, and exploited it to identify the floor number and to estimate the horizontal position of an unknown node. It is suitable for indoor environments with multiple floors and multiple walls. From the simulation results, the scheme achieved good accuracy, especially for the positioning of the planes. Based on the results, an improved method was utilized to increase the localization accuracy in parts of indoor areas. This method can work more efficiently if *a priori* information is available on interior structures and wall distribution.

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