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A New Positioning Scheme Exploiting RSS Difference of Arrival in Indoor Environments

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Abstract

Three basic properties of radio signal, such as received signal strength (RSS), time of flight, and angle of arrival, are commonly used in estimation of distance for positioning of a target. Among them, the positioning technique based on RSS attracts much more interests of researchers due to its high feasibility in realization. However, the performance of the conventional positioning scheme based on RSS is significantly degraded than that of TOA or fingerprinting scheme because of error components from multipath and shadowing effects. In this paper, the RSS-based positioning scheme, which defines RSS difference of arrival (RDOA) likewise time difference of arrival (TDOA) to mitigate error components, is proposed and its performance of position estimation is experimentally analyzed in indoor environments. The performance of the proposed RDOA scheme is compared with that of conventional scheme likewise TOA scheme with respect to the fixed AP selection case, the base AP changing case, and the adaptive AP selection case, respectively. According to the experiment results, it is shown that a high accuracy in position estimation also can be achieved with the RDOA scheme compared to the conventional scheme likewise TOA, while the RDOA scheme can provide less standard deviation than the conventional scheme.

Keywords*: Positioning, RSS, TDOA, TOA, WLAN*

1. Introduction

According to a report by Informa Telecoms & Media and the Wireless Broadband Alliance (WBA), it is expected that the number of Wi-Fi hotspots for public increases by 350% in the next four years [1]. With the increasing popularity of wireless networks, the positioning service for mobile devices likewise location-based service (LBS) has drawn considerable attention in recent years [2, 3, 4]. For an example, some hospitals have deployed the service solutions based on Wi-Fi for real-time positioning and tracking of equipment in order to increase utilization of equipment and to reduce costs of maintenance and purchase. In school, attendance of student can be tracked by tracking his/her Wi-Fi laptop or tablet PC. If a laptop or a tablet PC is lost, it can be also tracked throughout the campus by using the wireless local area networks (WLAN). In manufacturing field, goods can be tracked for shipping while they are moved to different locations inside and outside of warehouse.

All those applications and services utilizing wireless networks rely on location information, which describes the position of each target. To obtain the location information of a target, a two-step positioning algorithm is usually considered. In the first step, signal parameters, likewise TOA, RSS, AOA, TDOA, are measured. As the second step, then, the position of the unknown target is estimated with the signal parameters obtained in the first step. Positioning techniques using angle or time estimation are

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relatively complex to implement because of the difficulty of estimation especially in a multipath environment, compared to the RSS-based techniques [5, 6]. Moreover, the TOA-based scheme needs synchronization between the access point (AP) and target mobile devices, which makes the system more complex, while the TDOA-based scheme needs synchronization among APs. Meanwhile, the RSS-based positioning technique attracts much more interests of researchers due to its high feasibility in realization because the RSS values are easily recorded and can be collected in advance in wireless network. Therefore, RSS-based scheme is considered as the most suitable technique to estimate the position information of active targets in indoor environments such as offices, hospitals, shopping mall, and banks.

Generally, the RSS-based positioning scheme is a straightforward way to estimate the location of a target with distance estimation likewise TOA-based scheme or fingerprinting scheme. However, the performance of the conventional positioning scheme based on RSS is significantly degraded than that of TOA or fingerprinting scheme because of error components from multipath and shadowing effects [7, 8]. Moreover, the fingerprinting scheme needs a laborious works that have to collect RSS data for every spot ahead of time, which takes lots of time [9, 10].

In [11], the performance of the RSS-based scheme likewise TOA scheme was analyzed by considering various situations, such as different position and number of installed APs. Then a scheme selecting adaptively APs and a scheme changing base AP were introduced for enhanced performance. In this paper, the RSS-based positioning scheme exploiting RSS difference of arrival (RDOA) likewise TDOA is proposed and its performance of position estimation is experimentally analyzed in indoor environments.

The rest of the paper is organized as follows: Section 2 describes the experimental environments. Section 3 discusses the proposed RDOA positioning scheme. Section 4 compares the performance of the proposed RDOA scheme with that of conventional scheme likewise TOA scheme under various situations. Finally, conclusions are given in Section 5.

2. Experimental Environments

To evaluate the positioning performance of considered schemes in a real indoor radio propagation environment, the experiments were implemented in the ground floor of general building, located at Kwangwoon university. The dimensions of the test area are 11m by 9m with an area of 99m^2. Fig. 1 gives the layout of experiments. Note that the interval between grids is 0.5m. The six reference APs, from AP1 to AP6, are installed at fixed position in the test area. A target moves along the boundary of a rectangular space, which is with 6.5m by 6.5m. The blue line represents the boundary of the rectangular space and the red triangles indicate the position of reference APs, while the green quadrangles represent the measurement position of the target. The target was a laptop, Xnote-R500sp74k, equipped with surrounding antennas through screen. The AP was ZIO-AP1500N that operates in 2.4~2.4835GHz. Its output power was 20dBm. 802.11b/g/n WLAN scheme was considered. The target was fixed at 60cm height above ground in LOS environments. At each test point, the antenna of the laptop will receive all the signals from AP1 to AP6 at the same time. In order to raise accuracy, the measurement was repeated eight runs for every spot and then distance error was averaged to mitigate unstable values of RSS and Gaussian noise.

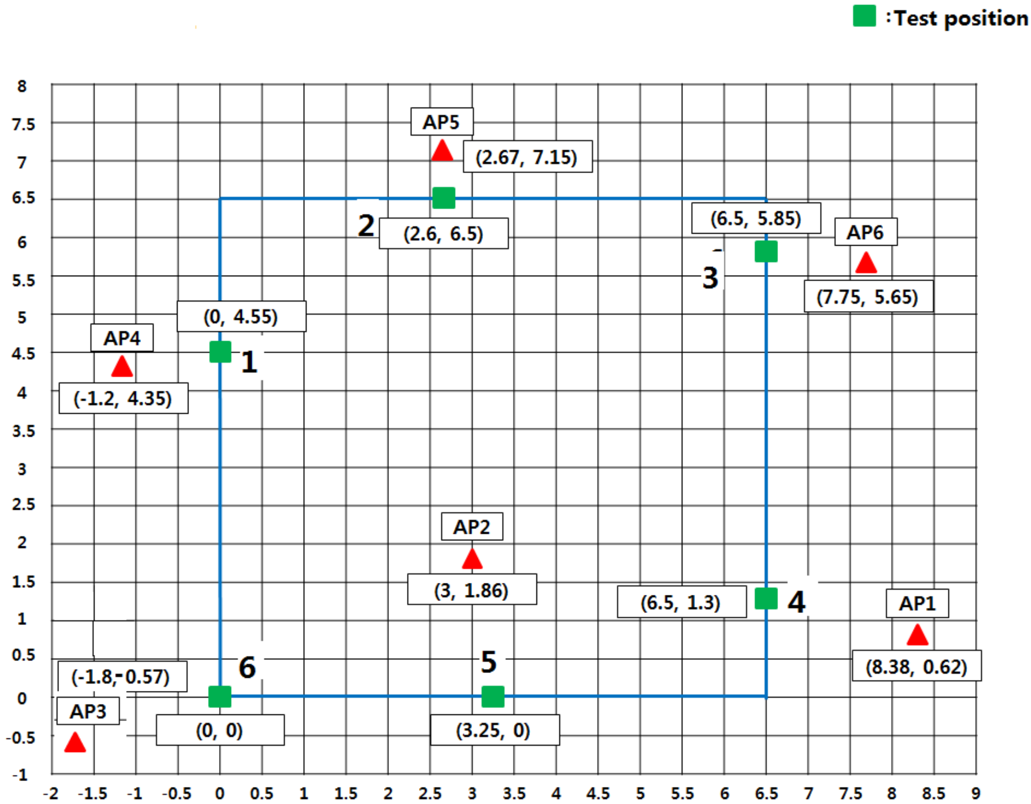

Figure 1. The Layout of Experiments (unit: meter)

3. Position Estimation Methods

3.1. TDOA-Based Position Estimation Method

In conventional TOA scheme, distance is estimated by using measurements of time of flight under assuming that the target and APs are synchronized. Given with the estimated distance, position of the target is estimated by finding a point of intersection of three circles. In conventional TDOA scheme, meanwhile, the measurements of time difference of arrival under assuming synchronization of APs is used for position estimation of target, which is estimated by finding a point of intersection of two hyperbolic curves. The measurement of TDOA provides the time difference when the signals from different reference APs are received. With the information of TDOA and known position of referencing APs, a hyperbola whose foci are at the known position of referencing APs can be defined and the estimated position of the target must lie on the hyperbola. In two-dimensional plane, at least three referencing APs are necessary to estimate the position of the unknown target. As shown in Fig. 2, under noisy environments, three different intersections can be obtained with three reference APs in TDOA positioning scheme. For examples, one estimated position is the intersection of hyperbola from AP2, AP3 and hyperbola from AP1, AP3 as shown in Fig. 2 (a).

By changing the benchmark AP3 to AP1, another estimated position, which is determined with the hyperbola from AP1, AP3 and the hyperbola from AP1, AP2, can be obtained as shown in Fig. 2 (b). Note that the third position is obtained with the hyperbola from AP2, AP3 and the hyperbola from AP1, AP2. Let (x_0, y_0) denotes the coordinate of the target, d_n denotes the distance between the target and reference AP n, and (x_n, y_n) denotes the coordinate of the referencing AP n. Then, the basic relations are derived as follows:

$$
\begin{aligned}
d_1^2 &= (x_1 - x_0)^2 + (y_1 - y_0)^2 \\
d_2^2 &= (x_2 - x_0)^2 + (y_2 - y_0)^2 \\
&\vdots \\
d_n^2 &= (x_n - x_0)^2 + (y_n - y_0)^2
\end{aligned} \qquad (1)
$$

where d_n is the distance between the target and the referencing AP n, and n is the total number of reference APs.

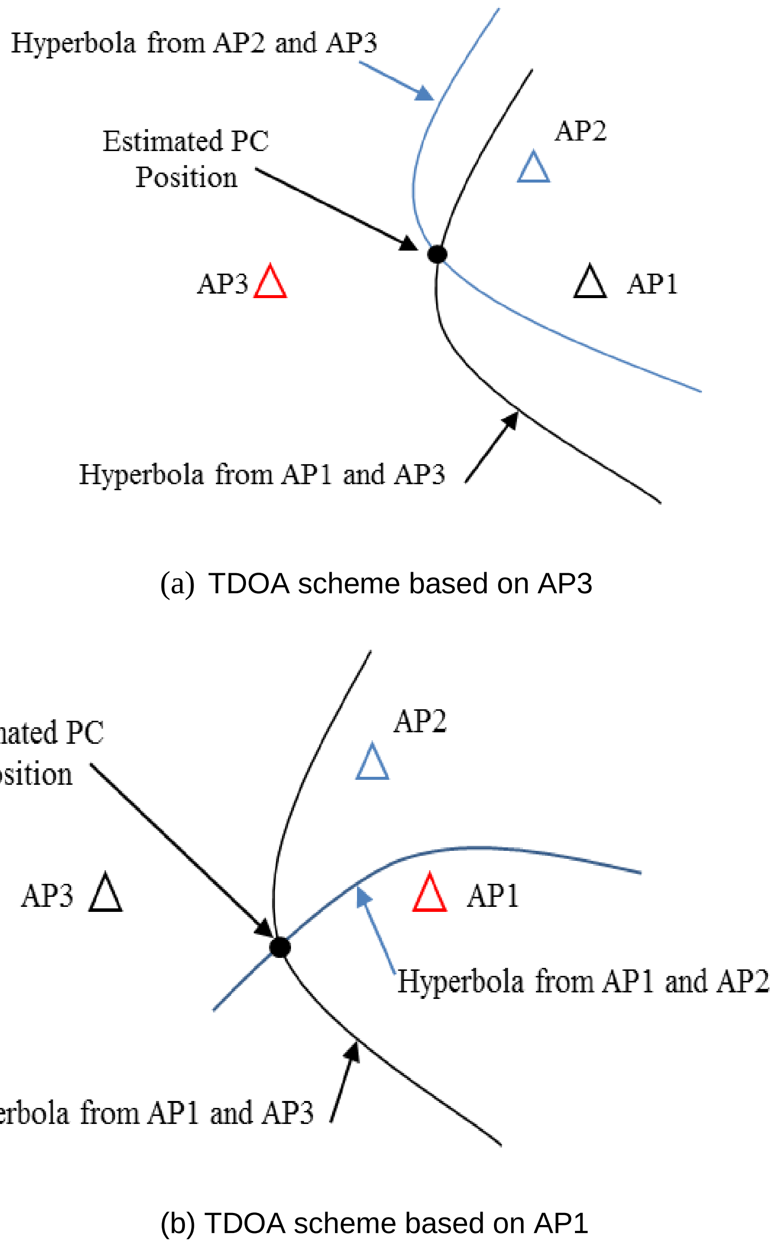

Figure 2. Principle of TDOA positioning scheme

When the difference of distance from a reference AP n to the reference AP1 is defined as $\Delta d_n = d_n - d_1$ and the AP1 is considered as the base AP, the above equations can be rewritten as:

$$\begin{aligned} d_1^2 &= (x_1 - x_0)^2 + (y_1 - y_0)^2 \\ (d_1 + \Delta d_2)^2 &= (x_2 - x_0)^2 + (y_2 - y_0)^2 \\ &\vdots \\ (d_1 + \Delta d_n)^2 &= (x_n - x_0)^2 + (y_n - y_0)^2 \end{aligned} \tag{2}$$

By subtracting the first equation from all the equations, (2) can be rewritten as

$$\begin{aligned} -(x_2 - x_1)x_0 - (y_2 - y_1)y_0 &= \Delta d_2 d_1 + \frac{1}{2}(\Delta d_2^2 - x_2^2 - y_2^2 + x_1^2 + y_1^2) \\ -(x_3 - x_1)x_0 - (y_3 - y_1)y_0 &= \Delta d_3 d_1 + \frac{1}{2}(\Delta d_3^2 - x_3^2 - y_3^2 + x_1^2 + y_1^2) \\ &\vdots \\ -(x_n - x_1)x_0 - (y_n - y_1)y_0 &= \Delta d_n d_1 + \frac{1}{2}(\Delta d_n^2 - x_n^2 - y_n^2 + x_1^2 + y_1^2) \end{aligned} \tag{3}$$

The above equations also can be rewritten in matrix from as follows:

$$\mathrm{Hx} = d_1 a + b, \tag{4}$$

where

$$\mathrm{H} = \begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \\ \vdots & \vdots \\ x_n - x_1 & y_n - y_1 \end{bmatrix}, \quad \mathrm{x} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}, \quad \mathrm{a} = \begin{bmatrix} -\Delta d_2 \\ -\Delta d_3 \\ \vdots \\ -\Delta d_n \end{bmatrix}, \quad \mathrm{b} = -\frac{1}{2}\begin{bmatrix} \Delta d_2^2 - x_2^2 - y_2^2 + x_1^2 + y_1^2 \\ \Delta d_3^2 - x_3^2 - y_3^2 + x_1^2 + y_1^2 \\ \vdots \\ \Delta d_n^2 - x_n^2 - y_n^2 + x_1^2 + y_1^2 \end{bmatrix}.$$

The least-squares estimation of this equation is given by

$$\hat{x} = (H^T H)^{-1} H^T (d_1 a + b). \tag{5}$$

3.2. Proposed RDOA-Based Position Estimation Method

The conventional RSS-based positioning technique likewise TOA scheme, which is termed as RSS of arrival (ROA) for convenience, also estimates the distance among the target and APs by using RSS measurements, and the position of the target is estimated by finding a point of intersection of three circles. Meanwhile, the RSS-based positioning scheme based on RSS difference likewise TDOA estimates the position of a target by finding a point of intersection of two hyperbolic curves. The RSS value from each AP is recorded at each measurement point and converted to the distance data based on log-normal shadowing model. Then the estimated coordinates of each point can be calculated with the same process as the above TDOA-Based method. For the RSS-based techniques, however, we can easily find ($d_1 a + b$) of the equation (5), and thus, by inserting $\Delta d_n = d_n - d_1$ into *a* and *b*, it can be rewritten as follows:

$$d_1 a + b = \frac{1}{2}\begin{bmatrix} x_2^2 + y_2^2 - d_2^2 - (x_1^2 + y_1^2 - d_1^2) \\ x_3^2 + y_3^2 - d_3^2 - (x_1^2 + y_1^2 - d_1^2) \\ \vdots \\ x_n^2 + y_n^2 - d_n^2 - (x_1^2 + y_1^2 - d_1^2) \end{bmatrix} \tag{6}$$

It is worth to notice that the equation (4) with the above result of equation (6) is the same with TOA-based scheme in [12], although the equation (4) is driven for TDOA scheme. In other words, regardless of the TOA-based or TDOA-based positioning schemes, the same positioning result will be obtained with the difference of distance $\Delta d_n = d_n - d_1$, when d_n is used as the measured distance based on the RSS_n value.

In this paper, the difference of RSS values is defined as $\Delta RSS_n = RSS_n - RSS_1$ and it is used for RDOA scheme in our experiments. In the RSS-based method, as well known, the distances are computed based on log-normal shadowing model, which is mathematically described as

$$\mathrm{RSS[dBm]} = P_0 - 10 \times N \times \log\left(\frac{D}{D_0}\right) \tag{7}$$

where D_0 is 1m, P_0 is the RSS value at reference distance, and the loss coefficient is set to N (=1.6). If the RSS value is measured, the distance between the target and the AP can be calculated as follows:

$$D = D_0 \cdot 10^{\left(\frac{P_0 - RSS}{10 \cdot N}\right)}. \tag{8}$$

In real environments, however, the RSS value is affected by path loss and shadowing effects. The path loss relates to dissipation of signal power over distances, while shadowing results from reflection, scattering. Because of the impact of shadowing effects to the signal propagation in the indoor environment, the RSS tends to be weaker and more unstable as the distance between the receiver and transmitter increases, and it causes the increase of the estimation errors with the real distance [13, 14]. Therefore, the RSS value can be divided into two parts, real RSS value and error component, as follows:

$$\mathrm{RSS[dBm]} = P_n + I_n, \tag{9}$$

where P_n represents the real RSS value at the receiver from AP n, I_n is the error component from the physical effects on the measurement channel, such as multipath and shadowing effects. Therefore, the difference of RSS value, ΔRSS_n, between AP n and AP1 can be rewritten as follows:

$$\Delta RSS_n = RSS_n - RSS_1 = P_n + I_n - P_1 - I_1 = P_n - P_1 + \Delta I_n. \tag{10}$$

With the equations (8) and (10), the measured difference of distance, Δd_n, can be represented as follows:

$$\Delta d_n = D_0 \cdot 10^{\left(\frac{P_0 - \Delta RSS_n}{10 \cdot N}\right)}$$

$$=D_0 \cdot 10^{\left(\frac{P_0 - (P_n - P_1 + \Delta I_n)}{10 \cdot N}\right)} \tag{11}$$

Note that the difference of real RSS values, P_n-P_1, has more influence on the difference of distance, Δd_n, if the ΔI_n is a Gaussian random variable with zero mean. By plugging (11) into (5), therefore, the estimation position of target, $\hat{x}$, can be achieved.

4. Performance Evaluation through Experiments

4.1. Positioning Performance with Fixed APs Case

In this section, the errors of positioning schemes were evaluated through experiments with fixed APs. Three APs are selected to form a triangle and the inside errors were separated from the outside errors, if the target was placed inside the triangle or not. As shown in the Fig. 3, AP2, AP4, and AP5 form a triangle, while AP1, AP2 and AP6 form another triangle. The RSS were measured at six fixed testing spots, which are green quadrangles with numbering 1 to 6, for comparing the positioning error at inside and outside spots of these triangles. The positioning errors between estimated coordinate and real coordinate via RDOA and ROA methods are given in Table 1 and Table 2. For the triangle formed by AP245, the errors of the inside testing spots, spot 1 and spot 2, are much smaller than those of the outside testing spots, spot 3 and spot 4. Similarly, the testing spot 4, which is inside the triangle formed by AP126, has the smallest positioning error compared to other spots outside the triangle. Beside this, three different positioning errors at each testing spot can be calculated with different benchmarks of hyperbola. For a comparison, the positioning error based on ROA method is given on the right column of the Table. Figs. 4 and 5 provide comparison of the position error of the two methods at 6 different spots. Based on the experimental results, it can be deduced that the inside errors of the triangle were much lower than the outside errors. However, there is no big difference in three different positioning errors caused from the changes of hyperbola benchmark. In the following analysis, therefore, only the result with smallest positioning error will be given.

Table 1. Positioning Errors with AP245 based on RDOA and ROA Methods

	Error of RDOA method (m)			Error of ROA (m)
Test spot	Benchmark AP2	Benchmark AP4	Benchmark AP5	
1	**1.6909**	**1.6893**	**1.6907**	**2.0479**
2	**2.2581**	**2.2586**	**2.2573**	**2.4075**
3	5.0153	5.0180	5.0149	3.4521
4	5.7399	5.7438	5.7412	3.6119
5	4.6993	4.7002	4.7006	3.6720
6	4.7413	4.7405	4.7457	4.6640
Mean error	4.0241	4.0250	4.0251	3.3092
Std. devi.	3.6687	3.6720	3.6708	2.1173

Table 2. Positioning Errors with AP126 based on RDOA and ROA Methods

	Error of RDOA method (m)			Error of ROA (m)
Test spot	Benchmark AP1	Benchmark AP2	Benchmark AP6	
1	6.2951	6.2831	6.2846	106.7221
2	5.0118	5.0061	5.0058	9.6115
3	2.9961	2.9934	2.9927	9.4799
4	**1.6408**	**1.6417**	**1.6432**	**0.3753**
5	4.0297	4.0298	4.0346	12.1781
6	6.7179	6.7162	6.7200	6.1454
Mean error	4.4486	4.4451	4.4468	24.0854
Std. devi.	4.3641	4.3576	4.3591	90.9804

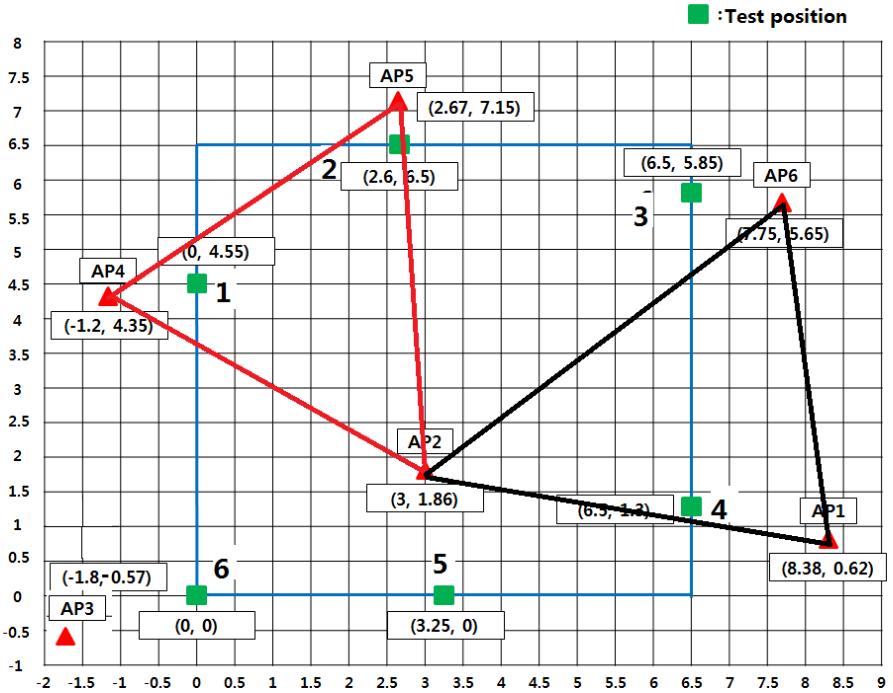

Figure 3. Placements of AP245 and AP126

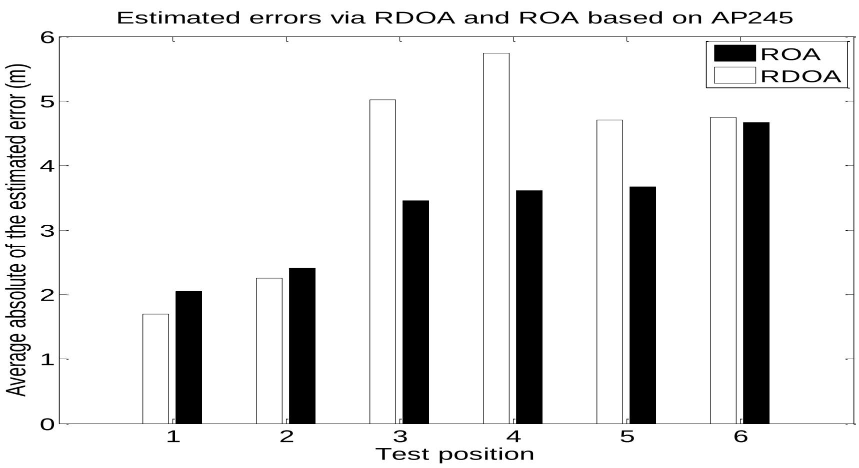

Figure 4. Comparison of Positioning Errors with AP245

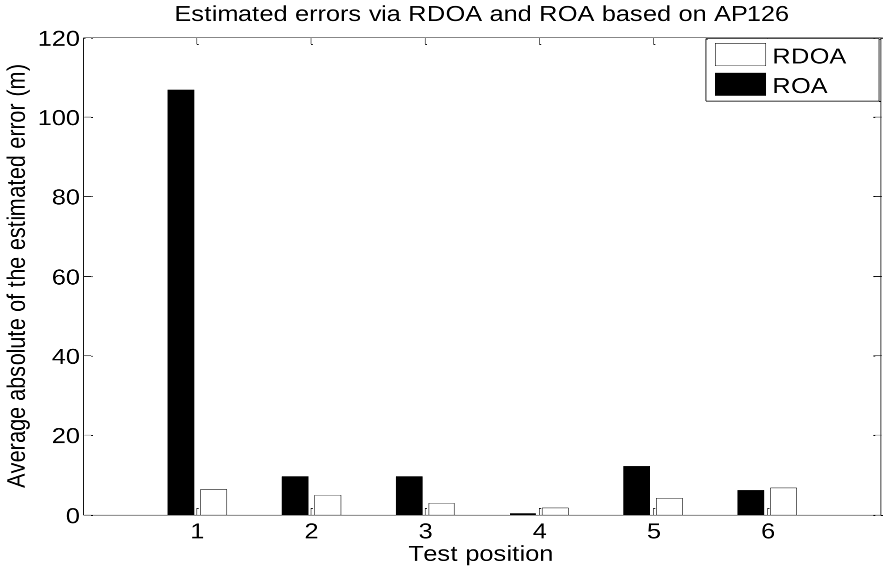

Figure 5. Comparison of Positioning Errors with AP126

4.2. Positioning performance with base AP changing case

Because of the movement of the target, in the realistic environment, it is difficult to decide if the target is inside or outside of the triangle formed by 3 fixed APs. As for the positioning performance in general situation, the positioning results at each test position were evaluated by all 6 reference APs. Among the 6 APs, the one with the largest RSS value at the receiver is selected as the base AP and then two other reference APs, which will be used in the RDOA method, are selected from the left 5 APs. Thus, 10 different estimated results, which are the number of combinations of 2 APs taken from 5 APs, are considered and are averaged at each test position. Table 3 provides the average estimated error at each position. For a comparison, the estimated results by using ROA-based method with the same base AP changing scheme are also given in the table. As shown in the table, the RDOA positioning method can achieve smaller mean error and standard deviation of errors, compared with ROA method. By comparing the positioning performance of the fixed APs case, moreover, it is shown that the performance of the base AP changing case is enhanced.

Table 3. Positioning Errors based on base AP Changing Scheme with all 6 Aps

Test position	Error of RDOA method (m)	Error of ROA (m)
1	3.6262	24.8178
2	3.6586	0.8510
3	3.6351	3.8843
4	2.4969	1.4020
5	5.2462	6.4022
6	3.1325	4.0663
Mean error	3.6326	6.9039
Std. devi.	2.0357	20.1305

4.3. Positioning Performance with Adaptive AP Selection Case

With the experiment results of RSS-based positioning method, it can be confirmed that a stronger RSS can enhance the performance of position estimation if APs are placed nearby targets. If the target is inside the triangle formed with three APs, moreover, the scheme using three APs can provide outstanding performance, compared to the scheme using 6 APs. It is because performance enhancement can be more achieved with a further reliable RSS value than with unreliable RSS values from more APs. With all the RSS values from six different APs, therefore, the adaptive AP selection method [11] is employed to evaluate the positioning performance of the RDOA scheme.

Table 4 provides the errors of RDOA and ROA methods based on adaptive scheme. By comparing with the previous two cases, the positioning performance is enhanced for both schemes. Note that it comes from the advantage of adaptive scheme. Under the adaptive scheme, a high accuracy can be achieved by the RDOA as well as the ROA techniques. However, it is worth to notice that the RDOA scheme can still provide less standard deviation than the conventional ROA scheme.

Table 4. Positioning Errors with Adaptive AP Selection Scheme

Test position	Error of RDOA method (m)	Error of ROA (m)
1	2.6945	1.5665
2	2.8052	1.4189
3	2.1915	1.1741
4	3.4334	3.5474
5	5.5427	4.6488
6	3.3789	4.2435
Mean error	3.3410	2.7667
Standard devi.	2.6236	3.4819

5. Conclusions

In this paper, the RSS-based positioning scheme exploiting the RSS difference likewise time TDOA is proposed and its performance of position estimation is experimentally analyzed in an indoor environment. The performance of the RDOA scheme is compared with that of conventional ROA scheme likewise TOA scheme with respect to the fixed AP selection case, the base AP changing case, and the adaptive AP selection case, respectively. According to the results, it is shown that the proposed RDOA positioning method can achieve smaller mean error and standard deviation of errors, compared with ROA method for the base AP changing case. As for the adaptive AP selection case, it is shown that a high accuracy in position estimation can be achieved with the RDOA scheme compared to the conventional ROA scheme, while the RDOA scheme can provide less standard deviation than the conventional scheme.

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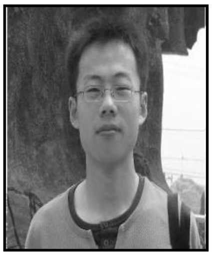

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