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Performance Improvement of IMR-Based NLOS Detection in Indoor Ultra Wide-Band TOA Localization

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SUMMARY Sensor networks, in which many small terminals are wirelessly connected, have recently received considerable interest according to the development of wireless technology and electronic circuit. To provide advanced applications and services by the sensor networks, data collection including node location is essential. Hence the location estimation is important and many localization schemes have been proposed. Time of arrival (TOA) localization is one of the popular schemes because of its high estimation accuracy in ultra wide-band (UWB) sensor networks. However, a non-line-of-sight (NLOS) environment between the target and the anchor nodes causes a serious estimation error because the time is delayed more than its true one. Thus, the NLOS nodes should be detected and eliminated for estimation. As a well-known NLOS detection scheme, an iterative minimum residual (IMR) scheme which has low calculation complexity is used for detection. However, the detection error exists in IMR scheme due to the measurement error. Therefore, in this paper, we propose a new IMR-based NLOS detection scheme and show its performance improvement by computer simulations.

key words: *sensor networks, UWB, TOA-based position estimation system, NLOS environment, IMR method*

1. Introduction

Global Positioning System (GPS) localization using medium earth orbit satellite which is currently a mainstream scheme has generally weakness of low accuracy in indoor estimation. Therefore, ultra wide-band (UWB) technology is also used widely because it can achieve high accuracy localization even in indoor environment [1]. In localization of mobile terminal, the received signals at sensor nodes from the mobile terminal and the location information of the sensor nodes are used. As the conventional localization schemes, there are some schemes such as time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA) and received signal strength (RSS) schemes [2]–[4]. In the indoor environment, the required accuracy is typically ones to tens centimeters and in UWB measurements, which has a higher time resolution, TOA scheme is recognized as the most suitable one [5]. In TOA scheme, the measurement distance is calculated by multiplying signal's time of arrival between sensors and mobile terminal with the speed of light. Then, using Maximum Likelihood (ML) method or Least Square (LS) method, the location of mobile terminal is obtained. In these localization systems of sensor networks, the most significant issue is how to mitigate the influence of non-line-of-sight (NLOS) environment. Figure 1 shows the NLOS transmission case. The target node of unknown position sends a beacon signal to the anchor node of known position and the distance between them is calculated by the difference of transmit and receive time. In the line-of-sight (LOS) environment, the direct wave is used for calculation and the exact distance is obtained, while in the NLOS environment, the direct wave is blocked by some obstacles and the reflected wave is received. In this case, the time is delayed and the distance is measured more than the true one. This error leads the degradation of position estimation accuracy. To tackle this NLOS problem, two types of modification scheme have been proposed. One is a corrective error minimization using all anchor nodes including NLOS ones [3]. This scheme can estimate the target position even if all anchor nodes are in NLOS environment. However, the NLOS error is not perfectly eliminated and the residual error degrades the estimation performance. The other is a detection and elimination of NLOS anchor nodes. The position estimation is conduced only by LOS anchor nodes. This scheme can raise the accuracy of estimation but the serious error occurs when the identification of NLOS nodes is failed. One of the popular NLOS identification scheme is an iterative minimum residual (IMR) scheme [6]. This scheme first estimates the position of target node using all anchor node data by LS estimation. Next one anchor node is eliminated and the LS position estimation is again conducted. If the latter is more accurate, then the node elimination is iterated. Thus, the IMR scheme finds the best estimation results by this iteration. However, the measurement data of LOS anchor nodes also include a LOS bias error and this LOS bias lowers the NLOS identification accuracy in IMR scheme. According to [5], the bias is added to the measure-

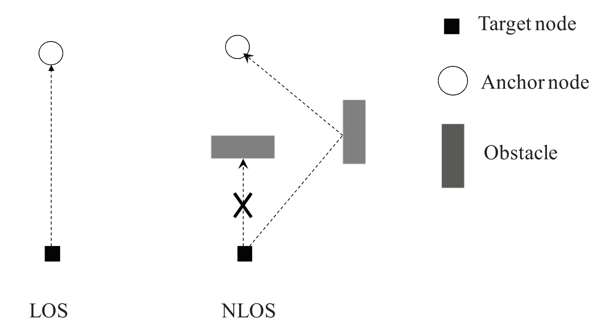

Fig. 1 Example of LOS and NLOS transmission.

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ment distance due to indoor multipath channels in the LOS environment.

Therefore, in this paper we propose an improved IMR-based NLOS detection scheme which increases the position estimation accuracy by minimizing the LOS bias error. In the following, the probability model of distance in LOS and NLOS environments is described in Sect. 2. IMR scheme and the proposed scheme are described in Sects. 3 and 4, respectively, simulation results are shown in Sect. 5, and the conclusion is drawn in Sect. 6.

2. Probability Model of TOA-Based Measurement Distance in LOS and NLOS Environments

2.1 Measurement Error in Indoor UWB Localization

In this section, let us consider the measurement error of UWB signal in TOA localization scheme in indoor environments. The measurement error mainly comes from the multipath reception in the receiver. In NLOS environments, the blocking of direct wave in addition to the multipath reception is the reason of the measurement error [5], [7]. Hence, a positive bias remains even after a large number of measurements and averaging in NLOS environments, which results in the performance degradation of localization. On the other hand, in LOS environments, no blocking occurs and there are lots of papers assuming that the mean value of measurement error is zero without considering the multipath bias. However, even in LOS environments, there is a positive bias. It is reported in [5] that the LOS bias occurs in UWB signal reception when the filter bandwidth is relatively narrow such as 500 MHz in the receiver, and the distance between the target and anchor nodes is longer than 10 m. When the filter bandwidth is narrow, the time resolution is reduced due to the narrow frequency span, and the peak of impulse response becomes loose. Then, the delay path components tend to be detected. Moreover, when the distance between the target and anchor nodes is long, the length of the direct wave and that of delay wave becomes similar, and the pathloss of direct wave is larger than that of remaining paths [8]. Thus, the ratio of direct wave power to the received signal power is decreased and the LOS bias is included in the measurement [5].

In the next subsection, we derive the probability model of TOA-based measurement distance with considering the LOS and NLOS biases.

2.2 Probability Model of Measurement Distance

We assume a two-dimensional sensor field in this study. Let (x, y) as the true address of target node to be estimated, N as the number of anchor nodes, (x_i, y_i) of $1 \le i \le N$ as the i-th anchor node address, and d_i as the true distance between the target node and i-th anchor node. Then, the measured distance at i-th anchor node $\hat{d}_i$ is given by

$$\hat{d}_i = d_i + \varepsilon_i \quad (i = 1, 2, \ldots, N) \tag{1}$$

where $d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ and the noise component ε_i is given by

$$\varepsilon_i = b_{i,LOS} + \xi_i b_{i,NLOS} \tag{2}$$

Here, $b_{i,LOS}$ and $b_{i,NLOS}$ are i-th error components in LOS and NLOS environments, respectively, and ξ_i is the switching parameter of 0 at LOS and 1 at NLOS environments [7]. These errors $b_{i,LOS}$ and $b_{i,NLOS}$ are Gaussian noises. The average $m_{i,LOS}$ and variance $\sigma^2_{i,LOS}$ of the LOS noise are given by

$$\begin{aligned} m_{i,LOS} &= m_{LOS} \log(1 + d_i) \\ \sigma^2_{i,LOS} &= \sigma^2_{LOS} \left[\log(1 + d_i)\right]^2 \end{aligned} \tag{3}$$

where m_{LOS} and σ^2_{LOS} are the LOS parameters dependent on the signal bandwidth. Similarly, $b_{i,NLOS}$ is characterized by $m_{i,NLOS}$ and $\sigma^2_{i,NLOS}$ which are given by

$$\begin{aligned} m_{i,NLOS} &= m_{NLOS} \\ \sigma^2_{i,NLOS} &= \sigma^2_{NLOS} \end{aligned} \tag{4}$$

where m_{NLOS} and σ^2_{NLOS} are the NLOS parameters dependent on the signal bandwidth as well. As shown in (4), the average and variance are not dependent on d_i in NLOS environment. From (2) to (4), the average and variance of Gaussian error ε_i are given by

$$\begin{aligned} m_i &= m_{LOS} \log(1 + d_i) + \xi_i m_{NLOS} \\ \sigma^2_i &= \sigma^2_{LOS} \left[\log(1 + d_i)\right]^2 + \xi_i \sigma^2_{NLOS} \end{aligned} \tag{5}$$

Finally, the conditional probability density function of measurement distance $\hat{d}_i$ is described by

$$p\left(\hat{d}_i | d_i\right) = \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{\left(\hat{d}_i - d_i - m_i\right)^2}{2\sigma^2_i}\right] \tag{6}$$

When the number of TOA measurement is M, the measurement distance is averaged as

$$\hat{d}_i = \frac{1}{M} \sum_{j=1}^{M} \hat{d}_{i,j} \tag{7}$$

where $\hat{d}_{i,j}$ is the j-th measurement distance at i-th anchor node.

3. Conventional IMR Scheme

IMR scheme is an iterative NLOS elimination scheme to find a minimum residual estimator (MRE) in LS estimation with various combinations of measured anchor nodes [6]. In the iteration a noisy anchor node is eliminated one by one. Let us consider N anchor node case. First, the LS-estimated location $\hat{\boldsymbol{\theta}} = (X, Y)$ and its normalized residual error $\bar{\varepsilon}(\hat{\boldsymbol{\theta}})$ is calculated by using N measurement data. The LS-estimated location $\hat{\boldsymbol{\theta}}$ is given by

$$\hat{\boldsymbol{\theta}}(X, Y) = \arg\min_{X,Y} \sum_{i=1}^{N} \left(\sqrt{(X - x_i)^2 + (Y - y_i)^2} - \hat{d}_i\right)^2 \tag{8}$$

where (X, Y) is the estimated target node address, (x_i, y_i) are the i-th anchor node address and $\hat{d}_i$ is obtained by the TOA measurement. Then, the normalized residual error is given by

$$\bar{\varepsilon}(\hat{\boldsymbol{\theta}}) = \frac{\varepsilon(\hat{\boldsymbol{\theta}})}{N_d} = \frac{1}{N_d}\sum_{i=1}^{N_d}\left(\hat{d}_i - \sqrt{(X-x_i)^2+(Y-y_i)^2}\right)^2 \quad (9)$$

where N_d is the number of anchor nodes used for calculation ($N_d = N$ at the beginning). $\varepsilon(\hat{\boldsymbol{\theta}})$ is normalized by N_d as shown in (9). Next, to eliminate one NLOS anchor node, LS position estimations are conducted ${}_NC_1 = N$ times with $N_d = N - 1$ measurement data and MRE $\hat{\boldsymbol{\theta}}'$ is derived. With comparing $\bar{\varepsilon}(\hat{\boldsymbol{\theta}})$ to $\bar{\varepsilon}(\hat{\boldsymbol{\theta}}')$, if $\bar{\varepsilon}(\hat{\boldsymbol{\theta}})$ is smaller than $\bar{\varepsilon}(\hat{\boldsymbol{\theta}}')$, $\hat{\boldsymbol{\theta}}$ is determined as the result of position estimation and the algorithm is end, otherwise let $N_d \to N_d - 1$ and MRE search and comparison is conducted with using $\bar{\varepsilon}(\hat{\boldsymbol{\theta}}')$. This operation is iterated until $N-3$ times or the error difference becomes less than threshold such as $|\bar{\varepsilon}(\hat{\boldsymbol{\theta}}) - \bar{\varepsilon}(\hat{\boldsymbol{\theta}}')| < \delta$. This δ is predetermined.

IMR algorithm is more effective in terms of calculation complexity when the number of anchor nodes N is large [6]. For example, when N=10 the optimal search needs the combination of

$$C = {}_NC_3 + {}_NC_4 + {}_NC_5 + \cdots + {}_NC_{10} = 1000 \quad (10)$$

searches, while if one of anchors should be eliminated with IMR algorithm, it only needs

$$C_{IMR} = 1 + {}_NC_1 = 1 + N = 11 \quad (11)$$

combination. If two anchors are eliminated, the combination becomes

$$C_{IMR} = 1 + {}_NC_1 + {}_{N-1}C_1 = 1 + N + N - 1 = 20 \quad (12)$$

which is still much less than C of (10). Hence, IMR scheme can find and eliminate NLOS anchors with less complexity. However, since LOS bias error exists and $\bar{\varepsilon}(\hat{\boldsymbol{\theta}})$ includes noise, the accuracy of NLOS identification becomes lower in IMR scheme. To tackle this problem, the modification scheme is proposed in the next section.

4. Proposed Scheme

Figure 2 shows the measured distance after sufficient number of beacon reception which means the measured distance sufficiently converges on the average m_i on (5). As described in Sect. 2, the measured distance includes bias components of $m_{i,LOS}$ and $m_{i,NLOS}$ even after sufficient measurements. Although the NLOS bias is usually larger, LOS bias also remains in many cases such as indoor severe multipath channels. By this bias IMR scheme may make misdetection of NLOS anchor nodes and degrades the performance for position estimation.

Therefore, we propose two types of bias reduction schemes: (a) proportional reduction and (b) LOS bias estimation [9]. In scheme (a), if the measured distance $\hat{d}$ is

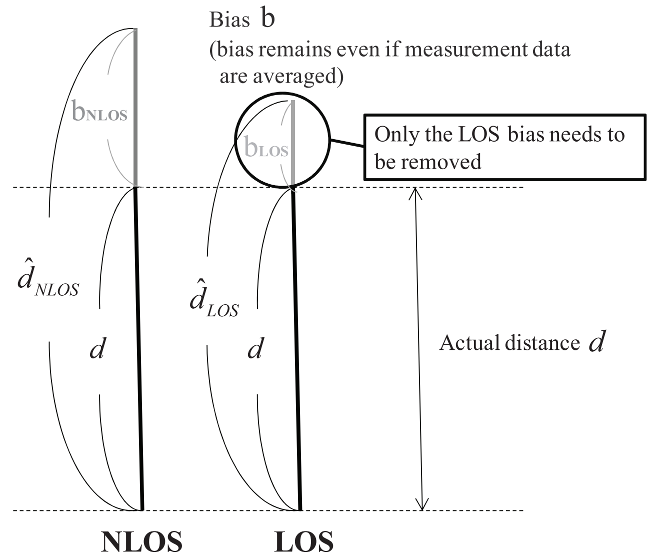

Fig. 2 Relationship between measured and actual distances.

smaller than 5 m, 8 percent of $\hat{d}$ is shortened as a LOS bias, and if $\hat{d}$ is over 5 m, 5 percent is shortened. These percentages were determined by heuristic search. In scheme (b), LOS bias is estimated and eliminated from the measured distance. From Sect. 2, the i-th measured distances $\hat{d}_{i,LOS}$ and $\hat{d}_{i,NLOS}$ in LOS and NLOS environments are described by

$$\begin{aligned}\hat{d}_{i,LOS} &= d_i + b_{i,LOS} = d_i + m_{LOS}\log(1+d_i)\\ \hat{d}_{i,NLOS} &= d_i + b_{i,LOS} + b_{i,NLOS} = d_i + m_{LOS}\log(1+d_i) + m_{NLOS}\end{aligned} \quad (13)$$

where d_i is the true distance between the target node and i-th anchor node, m_{LOS} and m_{NLOS} are the channel parameters. Since Eq. (13) includes the LOS bias in both LOS and NLOS environments, we define a new distance from the measured distance $\hat{d}_i$. The estimated LOS bias $\hat{b}_{i,LOS}$ is calculated by

$$\hat{b}_{i,LOS} = m_{LOS}\log(1+\hat{d}_i) \quad (14)$$

and the modified distances are derived from (13) by eliminating $\hat{b}_{i,LOS}$ as follows

$$\hat{d}_{i,prop} = \hat{d}_i - \hat{b}_{i,LOS} = \begin{cases}\hat{d}_{i,LOS,prop} = \hat{d}_{i,LOS} - \hat{b}_{i,LOS}\\ \qquad = \hat{d}_{i,LOS} - m_{LOS}\log(1+\hat{d}_{i,LOS})\\ \hat{d}_{i,NLOS,prop} = \hat{d}_{i,NLOS} - \hat{b}_{i,LOS}\\ \qquad = \hat{d}_{i,NLOS} - m_{LOS}\log(1+\hat{d}_{i,NLOS})\end{cases} \quad (15)$$

Then, the LOS bias $\hat{b}_{i,LOS}$ can be eliminated and the identification performance will be improved. To be exact, this subtraction is also executed for $\hat{d}_{i,NLOS}$, which is an undesired case. However, as shown in Fig. 2, $b_{i,NLOS}$ is larger than $b_{i,LOS}$ so that this oversubtraction in $\hat{d}_{i,NLOS}$ causes little degradation. We evaluate performances of the proposed scheme in the next section.

Although it is expected that the performance of scheme

(b) overcomes that of scheme (a), the estimation of channel coefficient m_{LOS} in (15) is needed in scheme (b), while scheme (a) does not require such parameter estimation and is easy for implementation.

Here, although the calculation complexity of IMR scheme is less than the optimal search, it is reported in [10] that the number of search in IMR scheme increases when the number of NLOS nodes or NLOS bias is large, and its reduction algorithm is also proposed. The calculation complexity of the proposed scheme is basically the same as IMR scheme because the search algorithm is not modified. Thus, it is expected that the application of reduction scheme in [10] is effective to the proposed scheme. However, due to space limitations, it will be considered in future studies.

5. Numerical Results

5.1 Simulation Conditions

In this section, to confirm the effectiveness of the proposed scheme, we evaluate the performances of IMR scheme in a NLOS environment. The NLOS detection performance and the root mean square error (RMSE) performance of position estimation are calculated throughout the sensor field shown in Fig. 3. The simulation conditions are listed in Table 1. The performances are evaluated where the target is located at all points at 0.1 m grid in $x-y$ field. It is assumed that NLOS anchor nodes are node 1, 3, and 8 regardless of the target node location. The number of beacon measurements per one detection and estimation is 30 and the number of trial at each target location is 1000. The maximum number of iteration in IMR scheme is $N-3$. It is assumed that the channel is a Gaussian channel with the parameter of Table 1 in both LOS and NLOS cases and that the measurement distance is observed with the probability density function of (6) at each anchor node. Here, in this system each anchor node doesn't know whether the measured distance is on LOS or on NLOS and it is estimated by IMR scheme. In scheme (a) it is assumed that the UWB bandwidth used in the system is known (for the reduction ratio configuration in Table 4), and in scheme (b) the channel parameter of m_{LOS} is assumed to be given perfectly. Also, it is assumed that the LOS and NLOS states do not change during M-time beacon measurements. In all schemes, the location estimation is conducted as follows. The target nodes sends beacon simultaneously to all anchor nodes M times, using the averaged distance of (7) NLOS node detection and elimination are conducted by IMR algorithm, and the coordinate of the target node is calculated. The performances of node detection and average RMSE are evaluated in the following.

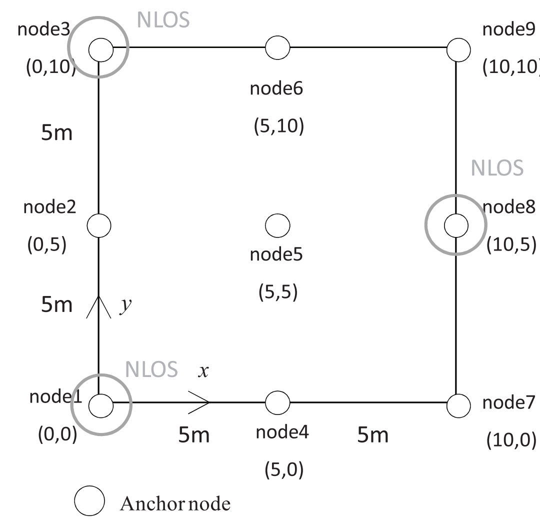

Fig. 3 Sensor field (NLOS node 3).

Table 1 Simulation conditions.

Sensor field range	10[m]×10[m]
Number of anchor nodes	$N=9$
Target node position	all points at 0.1[m] grid
NLOS Anchor node position	node1,3,8 (Fig. 3)
Number of TOA measurement per 1 trial	$M=30$ times
Number of NLOS detection trial	1000 times
Bandwidth	500[MHz] (UWB)
Mean and variance of noise(LOS)	$m_{LOS}\log(1+d), \sigma_{LOS}\log(1+d)$ ($m_{LOS}=0.21[m], \sigma_{LOS}=0.269[m]$ d : actual distance) [7]
Mean and variance of noise (NLOS)	$m_{NLOS}=1.62[m], \sigma_{NLOS}=0.809[m]$ [7]
Threshold δ	$\lvert\bar{\varepsilon}_0(\hat{\boldsymbol{\theta}})-\bar{\varepsilon}_1(\hat{\boldsymbol{\theta}})\rvert/10$ $\bar{\varepsilon}_0(\hat{\boldsymbol{\theta}})$: (9) with N nodes $\bar{\varepsilon}_1(\hat{\boldsymbol{\theta}})$: (9) with $N-1$ nodes
Maximum number of iteration in IMR scheme	$N-3$

5.2 Simulation1: Three NLOS Nodes

The number of NLOS detection failure out of 1000 trial is counted and plotted as shown in Figs. 4 to 6. The average numbers of NLOS detection failure are listed in Table 2. In those figures, black plots show that the NLOS detection error often occurs. In the conventional IMR scheme of Fig. 4, it is shown that the black plots are widely distributed in the center and edge areas. The degradation of the center area comes from the apparent NLOS bias decrease. The LOS and NLOS bias is decreased at the center by vector summation executed in LS estimation algorithm which results in the error decrease [2], [11]. Then, the detection algorithm of (9) doesn't work correctly in this case, because $\bar{\varepsilon}(\hat{\boldsymbol{\theta}})$ becomes similar value. In the edge area, since the performance of LS estimation is degraded [4], [11] the detection performance is

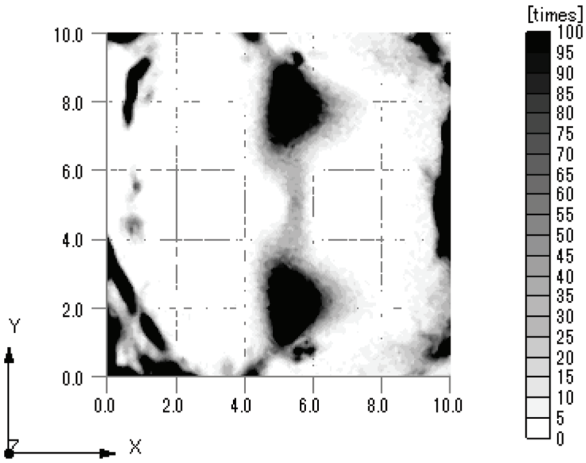

Fig. 4 NLOS detection performance of IMR scheme.

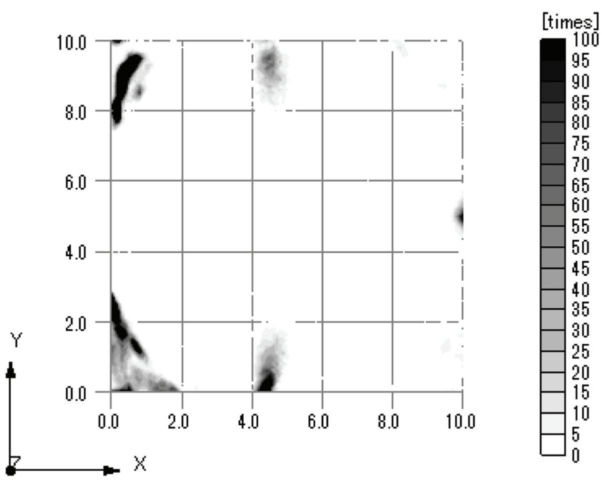

Fig. 5 NLOS detection performance of proposed scheme (a).

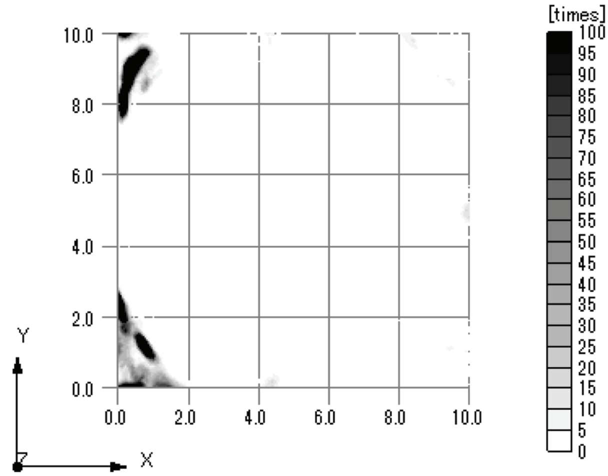

Fig. 6 NLOS detection performance of proposed scheme (b).

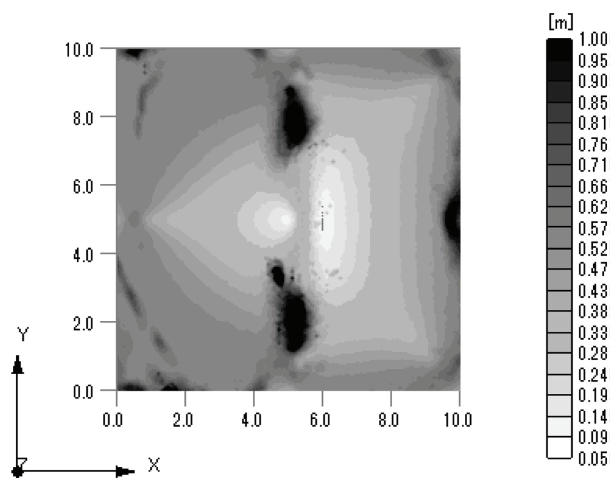

Fig. 7 RMSE performance of IMR scheme.

Table 2 Average misdetection of NLOS anchor out of 1000 trials.

Conventional IMR	Scheme (a)	Scheme (b)
34 times	5 times	3 times

also degraded.

Meanwhile, as shown in Figs. 5 and 6, the detection performances are improved in the proposed schemes (a) and (b). In particular, the scheme (b) can correctly detect the NLOS in all area except left part, because the scheme (b) effectively remove the LOS bias by estimating $\hat{b}_{i,LOS}$ from the measurement distance $\hat{d}_{i,LOS}$. It is more exact LOS bias than the percentage scheme of scheme (a). In Table 2 the average number of NLOS detection failures out of 1000 is 3 when using scheme (b), so we can see that this scheme effectively improve the NLOS detection performance.

Next, in the same simulation of Figs. 4 to 6, the RMSE performances are calculated. The results are shown in Figs. 7 to 9 and the average RMSE values in all fields are listed in Table 3.

Similar to Figs. 4 to 6, the black and white plots show high and low RMSE values, respectively. From the results, it is shown that the RMSE performances are highly correlated to the NLOS detection performance and the proposed scheme also improves the RMSE performances. The RMSE at the edge of sensor field is degraded in all schemes. This is because the performance of LS estimation tends to be lower at the edge in a mesh-type sensor field [4], [11].

The average RMSE in Table 3 shows that the proposed scheme can lower the RMSE less than 1/5 compared to the conventional IMR, in particular, that of scheme (b) is 0.083 m. Therefore, it was confirmed that the IMR scheme is improved by the proposed schemes.

Here, we investigate the generality of the effect of scheme (a). The reduction ratio of 0.08 and 0.05 for the measurement distance under and over 5 m, respectively, is derived by a heuristic search as described in Sect. 4. Figure 10 shows the RMSE versus various reduction ratio of scheme (a) in Simulation 1. It can be seen that the RMSE is convex function and the optimal configuration in terms

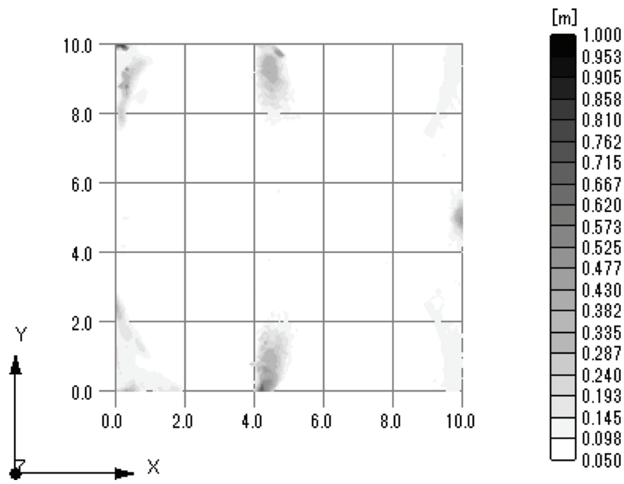

Fig. 8 RMSE performance of proposed scheme (a).

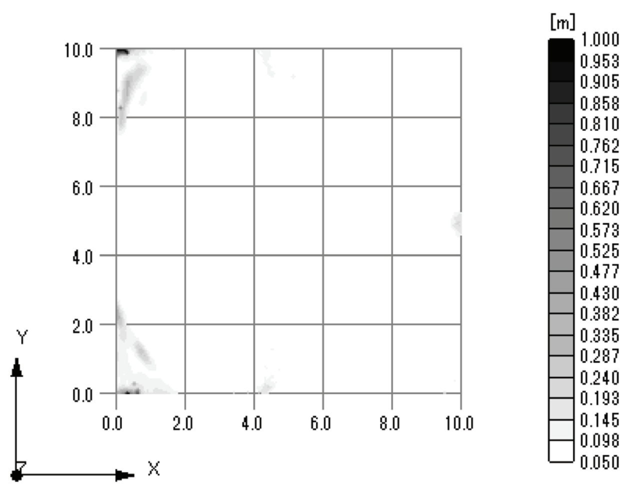

Fig. 9 RMSE performance of proposed scheme (b).

Table 3 Comparison of average RMSE[m] in sensor field.

Conventional IMR	Scheme (a)	Scheme (b)
0.484	0.094	0.083

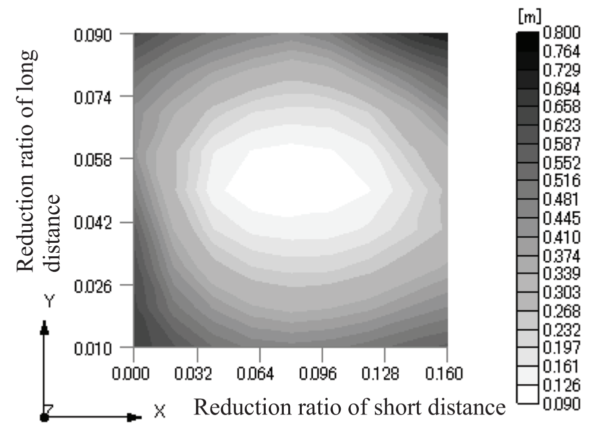

Fig. 10 Average RMSE for various reduction ratio parameters in Scheme (a).

Table 4 RMSE performances for various UWB bandwidth and their optimal parameters for Scheme (a).

UWB bandwidth [Hz]		200M	1G	2G
RMSE of Conv. IMR [m]		1.236	0.195	0.041
Reduction ratio of Scheme (a)	under 5m	0.16	0.038	0.005
	over 5m	0.11	0.026	0.006
RMSE of Scheme (a) [m]		0.173	0.043	0.016
RMSE of Scheme (b) [m]		0.166	0.038	0.015

of reduction ratio for short and long distance is found at 0.08 and 0.05, respectively. For simplicity the threshold distance of 5 m is fixed in this consideration and we search the optimal reduction ratio configuration for different channel environments, i.e., UWB bandwidths. Using the channel model of [7], the RMSE performances and the optimal configuration are heuristically investigated. The results of Table 4 show that the optimal configuration of scheme (a) is changed according to the bandwidth, which means the best performance is obtained when the system knows the UWB bandwidth of beacon. The average RMSE of the proposed schemes (a) and (b) is better than the conventional IMR scheme in all bandwidth conditions and it is confirmed that the proposed scheme is effective for various UWB channels. In general case, the optimal configuration can be obtained by doing the similar search in advance.

5.3 Simulation 2: Four NLOS Nodes

Next, to confirm whether the proposed scheme can improve the performance in many NLOS-node environment or not, we evaluate the performance of the proposed scheme in the field with four of nine NLOS nodes. With the same sensor field of Simulation 1, it is assumed that nodes 1, 3, 7, and 9 are on NLOS. The NLOS detection performances and their RMSE performances are calculated under the same condition of Table 1. Figures 11 and 12 show the number of NLOS detection failures and the average number of them in all field out of 1000 trials is listed in Table 5. The result of scheme (a) is omitted since it is similar to that of scheme (a).

From the result of Fig. 11 we can see that the performance becomes almost symmetry in the field and becomes better in the center area except around $x = 5$ or $y = 5$. The reason why the detection error occurs at $x = 5$ or $y = 5$ is the same as Simulation 1; the vector summation effect decreases the NLOS error in those areas in LS estimation and it makes

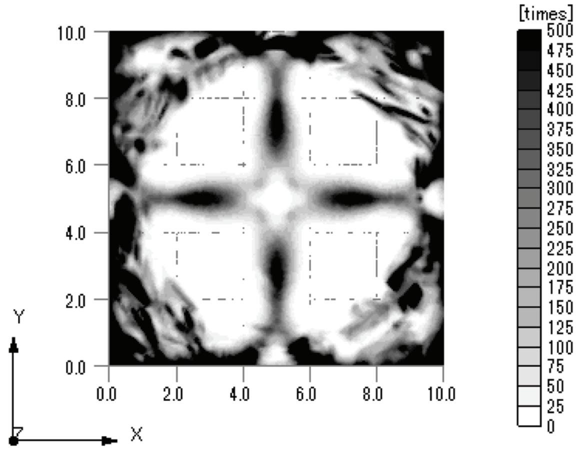

Fig. 11 NLOS detection performance of IMR scheme.

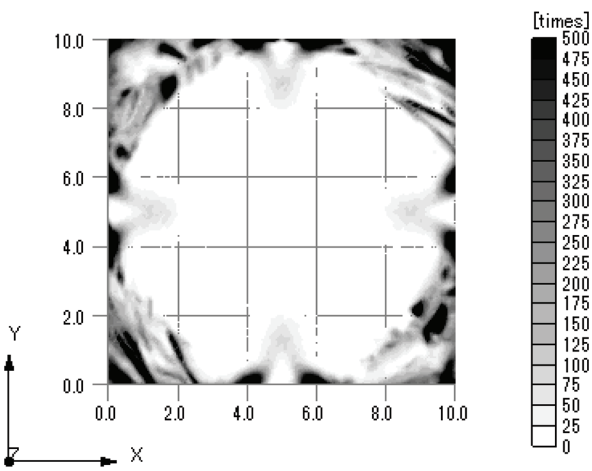

Fig. 12 NLOS detection performance of proposed scheme (b).

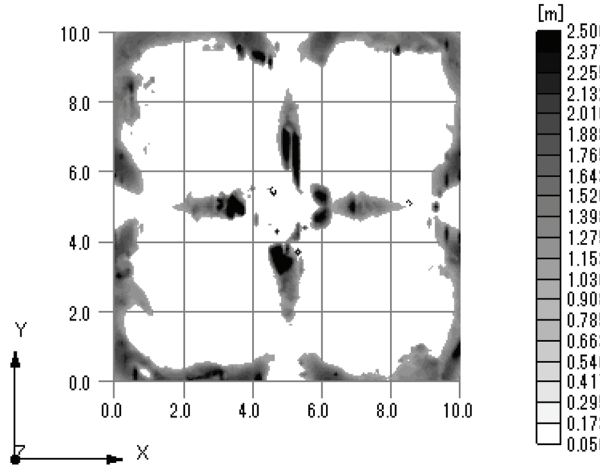

Fig. 13 RMSE performance of IMR scheme.

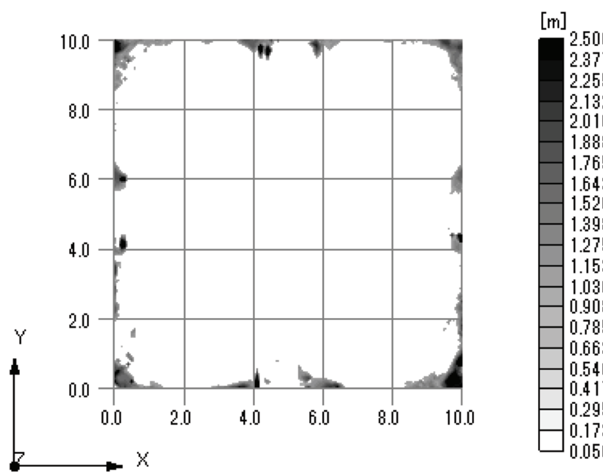

Fig. 14 RMSE performance of proposed scheme (b).

Table 5 Average misdetection of NLOS anchor out of 1000 trials.

Conventional IMR	Scheme (a)	Scheme (b)
224 times	89 times	86 times

Table 6 Comparison of average RMSE[m] in sensor field.

Conventional IMR	Scheme (a)	Scheme (b)
0.824	0.297	0.286

hard to distinguish NLOS nodes in IMR scheme. Also in the edge areas of the field, the detection performance is degraded because LS estimation in the lattice-shaped sensor field as shown in Fig. 3 has an error in those areas. As shown in Fig. 12, the detection error in the center area is resolved in the proposed schemes (b). From the results of Table 5 it is confirmed that the scheme (b) has the best performance also in the many NLOS-node environment.

Then, we calculated the RMSE performances corresponding to Figs. 11 and 12. The results are shown in Figs. 13 and 14. The result of scheme (a) is omitted since it is similar to that of scheme (a). We can see that the RMSE is correlated to the NLOS detection performance and the proposed schemes improve the RMSE performance. In particular, the RMSE in the edge area is also improved. The average RMSE in all fields is listed in Table 6, which shows that the RMSE of the proposed scheme is less than half of the conventional IMR scheme and the scheme (b) has the best performance. Consequently, the proposed scheme can improve the performance even in many NLOS-node environments.

5.4 Average RMSE Performance Versus the Number of Measurements

To confirm whether the proposed scheme can improve the performance at any measurement number M or not, we calculate the average RMSE of all sensor field versus M from 5 to 50. Figures 15 and 16 show the results of Simulation 1 and 2, respectively.

We can see that the proposed schemes outperform the

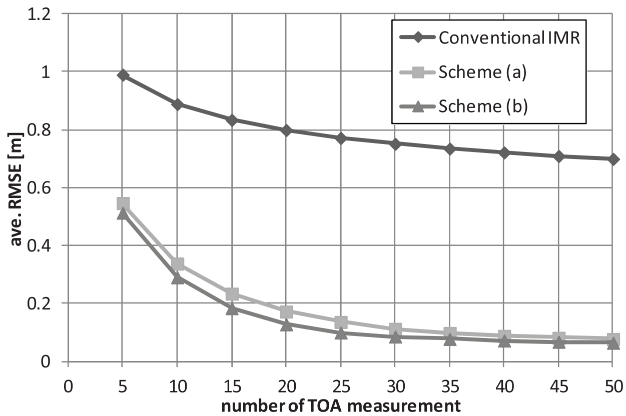

Fig. 15 Average RMSE performance versus number of measurements *M* in Simulation 1. (three NLOS nodes)

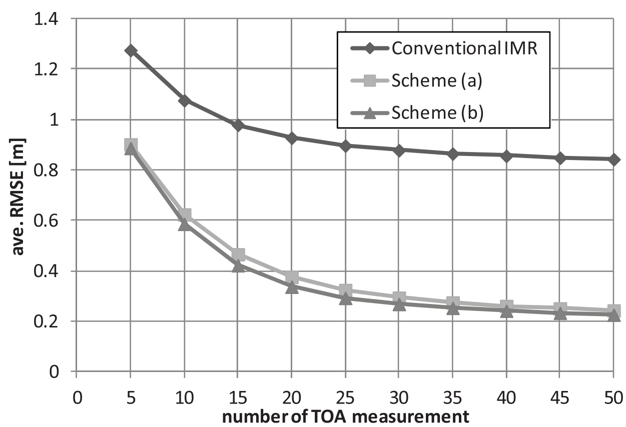

Fig. 16 Average RMSE performance versus number of measurements *M* in Simulation 2. (four NLOS nodes)

conventional scheme at any measurement number M. At $M = 5$, which is the least measurement case, the performance of the scheme (b) is 1.9 times and 1.4 times accurate than the conventional scheme, respectively. Thus, it was confirmed that the proposed scheme improved the RMSE performance regardless of the measurement number M.

5.5 Performance against the Increase of NLOS Nodes

The performance of the proposed scheme against the increase of NLOS nodes is evaluated. In the conditions of Table 1, it is assumed that the number of NLOS nodes is increased in numerical order of node-index from node 1. The average RMSE versus the number of NLOS nodes is depicted in Fig. 17. It is shown that along with the increase of NLOS nodes the performances are deteriorated in all schemes and the proposed schemes keep the better performance in any cases. Although it was expected the effect of the proposed scheme was decreased as the number of NLOS increased since the proposed scheme eliminated the LOS bias from measurement distance. However, it is found that the performance is improved regardless of the number of NLOS nodes, which means the LOS bias elimination is

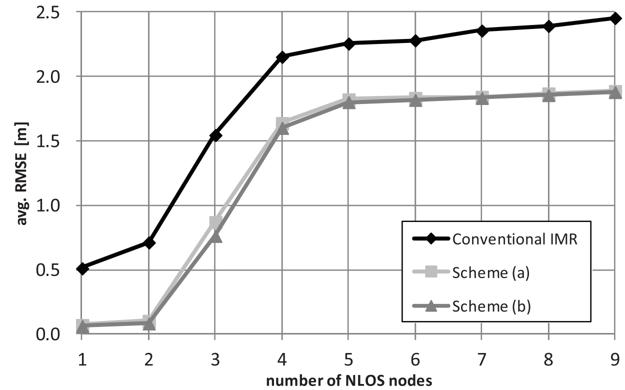

Fig. 17 Average RMSE performance versus number of NLOS nodes.

effective for both of LOS and NLOS nodes under the UWB transmission model of (2).

6. Conclusions

In this paper, we proposed an IMR-based improved NLOS detection scheme to raise the RMSE performance in TOA localization. By eliminating the LOS bias from the measured distance, the effect of IMR scheme which excluding NLOS anchor nodes in LS estimation can be enlarged and more exact NLOS detection was achieved. The numerical results showed that among three schemes of conventional IMR, proposed (a) and proposed (b), the proposed scheme (b) had the best performance of NLOS detection, resulting in the best RMSE performance because the estimated LOS bias was relatively accurate.

Then, we investigated the performance of the proposed scheme in many NLOS-node environments with various numbers of measurements and confirmed that both NLOS detection and RMSE performances were also improved. In comparison of scheme (a) and (b), the scheme (b) achieves the best performance but it needs the propagation parameter of m_{LOS}. Therefore, if we cannot obtain the parameter, the scheme (a) is a practical scheme in implementation.

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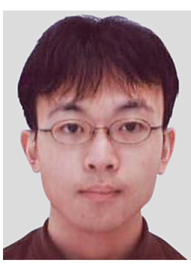

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