

Performance Improvement of TOA localization using IMR-based NLOS Detection in Sensor Networks

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Abstract—The sensor network with many small terminals communicating each other can cooperatively collect wider and variety of information and is expected to provide advanced services. To serve such new applications, the position information of targets is essential and the exact localization techniques are necessary. Time of arrival (TOA) localization is one of the popular schemes because of its high estimation accuracy. In TOA scheme, the target node of unknown position sends a signal to the anchor nodes of known position, from the arrival time stamps of the received signal the distance between the target and the anchor nodes is derived, and then, the estimated position is obtained. 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.

Keywords—Sensor Networks; TOA-based position estimation system; NLOS enviroment; IMR method

I. INTRODUCTION

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 [1][2].

As the conventional schemes, time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA) and received signal strength (RSS) schemes are used for localization. In those schemes, TOA is often used because of its high accuracy [3]. However, in practical situations, the accuracy of TOA scheme is often degraded by non-line-of-sight (NLOS) nodes. Fig. 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 times. 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 [4]. 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 conducted 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 least square (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.

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 Section II. IMR scheme and the proposed scheme are described in Section III and IV,

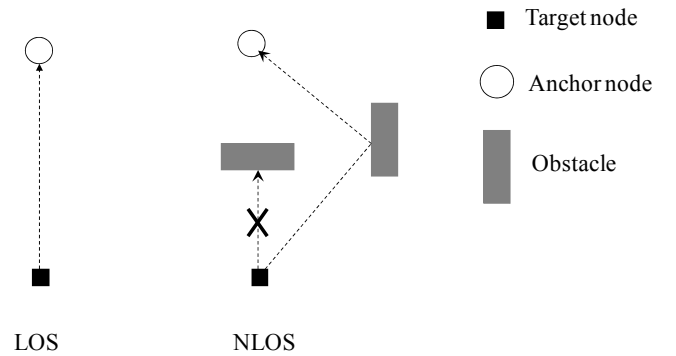


Fig. 1. Example of LOS and NLOS transmission.

respectively, simulation results are shown in Section V, and the conclusion is drawn in Section VI.

II. PROBABILITY MODEL OF TOA-BASED MEASUREMENT DISTANCE IN LOS AND NLOS ENVIRONMENTS

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 $1 \leq i \leq N$ 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

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

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

$$\varepsilon_i = b_{i,LOS} + \xi_i b_{i,NLOS} \quad (2)$$

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 [5]. These errors $b_{i,LOS}$ and $b_{i,NLOS}$ are Gaussian noises. The average $m_{i,LOS}$ and variance $\sigma_{i,LOS}^2$ of the LOS noise are given by

$$m_{i,LOS} = m_{LOS} \log(1 + d_i), \quad \sigma_{i,LOS}^2 = \sigma_{LOS}^2 [\log(1 + d_i)]^2 \quad (3)$$

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

$$m_{i,NLOS} = m_{NLOS}, \quad \sigma_{i,NLOS}^2 = \sigma_{NLOS}^2 \quad (4)$$

where m_{NLOS} and σ_{NLOS}^2 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

$$m_i = m_{LOS} \log(1 + d_i) + \xi_i m_{NLOS} \quad (5)$$

$$\sigma_i^2 = \sigma_{LOS}^2 [\log(1 + d_i)]^2 + \xi_i \sigma_{NLOS}^2$$

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

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

III. 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 $\hat{\mathbf{\theta}} = (X, Y)$ and its normalized residual error $\bar{\varepsilon}(\hat{\mathbf{\theta}})$ is calculated by using N measurement data. The LS-estimated location $\hat{\mathbf{\theta}}$ is given by

$$\hat{\mathbf{\theta}}(X, Y) = \arg \min_{X, Y} \sum_{i=1}^N \left(\sqrt{(X-x_i)^2 + (Y-y_i)^2} - \hat{d}_i \right)^2 \quad (7)$$

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

$$\bar{\varepsilon}(\hat{\mathbf{\theta}}) = \frac{\varepsilon(\hat{\mathbf{\theta}})}{N_d} = \frac{1}{N_d} \sum_{i=1}^{N_d} (\hat{d}_i - \sqrt{(X-x_i)^2 + (Y-y_i)^2})^2 \quad (8)$$

where N_d is the number of anchor nodes used for calculation ($N_d = N$ at the beginning). $\varepsilon(\hat{\mathbf{\theta}})$ is normalized by N_d as shown in (8). Next, to eliminate one NLOS anchor node, LS position estimations are conducted ${}_N C_1 = N$ times with $N_d = N-1$ measurement data and MRE $\hat{\mathbf{\theta}}'$ is derived. With comparing $\bar{\varepsilon}(\hat{\mathbf{\theta}})$ to $\bar{\varepsilon}(\hat{\mathbf{\theta}}')$, if $\bar{\varepsilon}(\hat{\mathbf{\theta}})$ is smaller than $\bar{\varepsilon}(\hat{\mathbf{\theta}}')$, $\hat{\mathbf{\theta}}$ is determined as the result of position estimation and the algorithm is end, otherwise let $N_d \rightarrow N_d - 1$ and MRE search and comparison is conducted with using $\bar{\varepsilon}(\hat{\mathbf{\theta}}')$. This operation is iterated until a certain number before at least three nodes remain to enable the position estimation.

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

$$C = {}_N C_3 + {}_N C_4 + {}_N C_5 + \dots + {}_N C_{10} = 1000 \quad (9)$$

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

$$C_{IMR} = 1 + {}_N C_1 = 1 + N = 11 \quad (10)$$

combination. If two anchors are eliminated, the combination becomes

$$C_{IMR} = 1 + {}_N C_1 + {}_{N-1} C_1 = 1 + N + N - 1 = 20 \quad (11)$$

which is still much less than C of (9). Hence, IMR scheme can find and eliminate NLOS anchors with less complexity. However, since LOS bias error exists and $\bar{\varepsilon}(\hat{\mathbf{\theta}})$ 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.

IV. PROPOSED SCHEME

Fig. 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 Section II, 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. In scheme (a), if the measured distance \hat{d} is smaller than 5m, 8 percent of \hat{d} is shortened as a LOS bias, and if \hat{d} is over 5m, 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 Section II, the i -th measured distances $\hat{d}_{i,LOS}$ and $\hat{d}_{i,NLOS}$ in LOS and NLOS

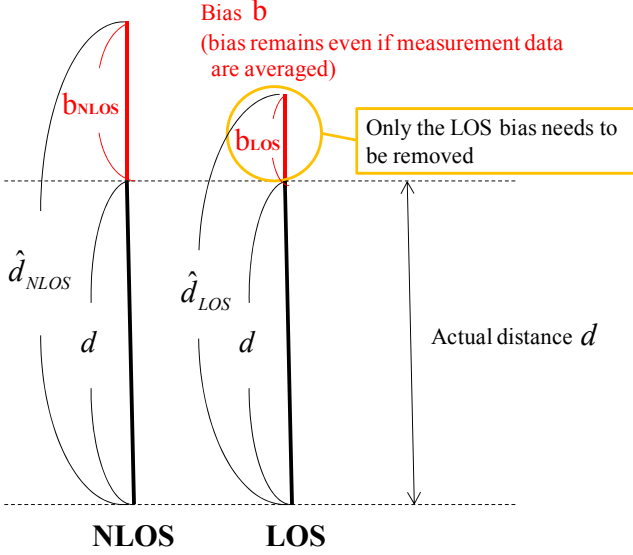


Fig. 2. Relationship between measured and actual distances.

environments are described by

$$\hat{d}_{i,LOS} = d_i + b_{i,LOS} = d_i + m_{LOS} \log(1 + d_i) \quad (12)$$

$$\hat{d}_{i,NLOS} = d_i + b_{i,LOS} + b_{i,NLOS} = d_i + m_{LOS} \log(1 + d_i) + m_{NLOS}$$

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. (12) 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

$$\hat{b}_{i,LOS} = m_{LOS} \log(1 + \hat{d}_i) \quad (13)$$

and the modified distances are derived from (12) by eliminating $\hat{b}_{i,LOS}$ as follows

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

$$\hat{d}_{i,NLOS,prop} = \hat{d}_{i,NLOS} - \hat{b}_{i,LOS} = \hat{d}_{i,NLOS} - m_{LOS} \log(1 + \hat{d}_{i,NLOS})$$

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.

V. NUMERICAL RESULTS

A. Conventional scheme

First, to confirm the NLOS misdetection and its influence to the position estimation accuracy in IMR 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 Tab. 1. The performances are evaluated where the target is located at all points at 0.1m

grid in $x - y$ field. For simplicity, it is assumed that NLOS anchor node is only node1 as shown in Fig. 3. The number of beacon measurements per one detection and estimation is 10 and the number of trial at each target location is 1000. The maximum number of iteration in IMR scheme is 1. The number of NLOS detection failure out of 1000 trial is counted and plotted as shown in Fig. 4. The results show that the detection failure increases in right upper area, which is a far side from the NLOS anchor node. It is because the LOS bias becomes large in proportion to its distance, while the NLOS bias is independent to the distance from the channel model described in Section II. Then, the ratio of LOS bias increases in the error component of measured distance compared to NLOS bias when the distance is large and the normalized residual error of (8) becomes incorrect which leads to the detection error.

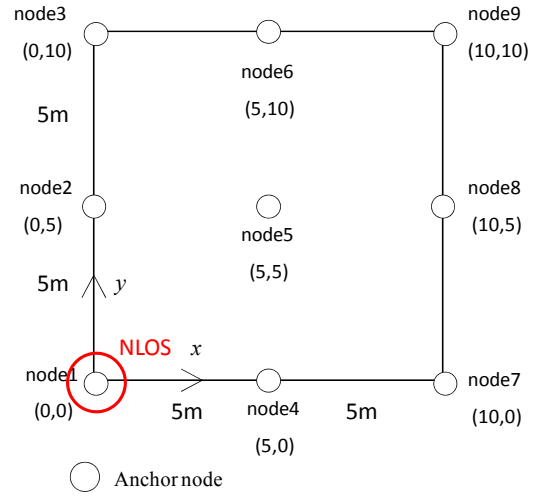


Fig. 3. Sensor field with one NLOS anchor.

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 (Fig. 3)
Number of TOA measurement per 1 trial	10 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) [5]
Mean and variance of noise (NLOS)	$m_{NLOS} = 1.62[m], \sigma_{NLOS} = 0.809[m]$ [5]
Number of iteration in IMR scheme	1

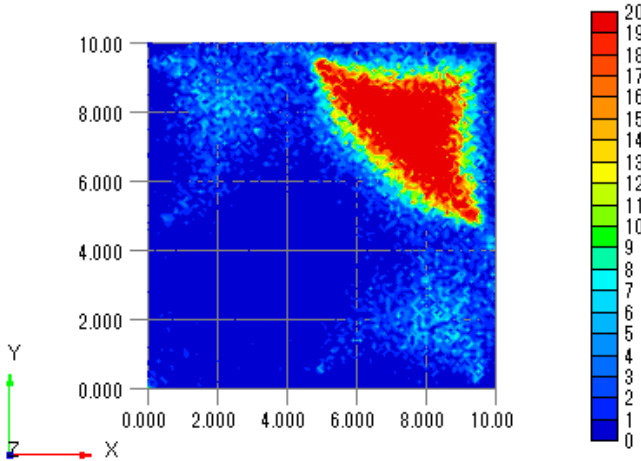


Fig. 4. NLOS detection performance of IMR scheme.

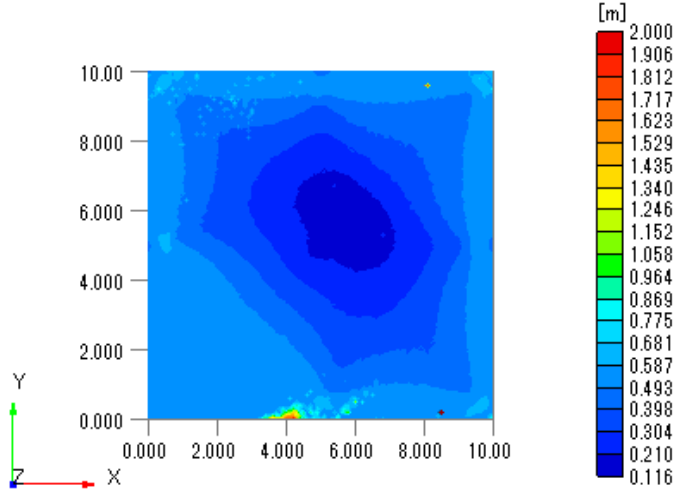


Fig. 5. RMSE performance of IMR scheme.

Using the same 10 measurement data, after NLOS detection by IMR scheme the LS position estimation is carried out with excluding the detected NLOS anchors. Fig. 5 shows the RMSE performance where blue dot shows the better performance and red means worse. From the result it is found that the RMSE is not always related to the NLOS detection performance. Conversely, the RMSE performance is degraded in the near area of NLOS anchor node regardless of NLOS detection error. This reason is discussed in the next subsection.

B. Proposed scheme

From the above results, we confirmed that the NLOS misdetection occurred in the far area from a NLOS anchor and the RMSE increases near the NLOS anchor node in IMR scheme. Next, to evaluate the performance of the proposed scheme in more general NLOS scenario, the performances in the three NLOS sensor field are calculated where the NLOS anchor nodes are node1, 3, and 8 as shown in Fig. 6. The maximum number of IMR iteration is three and other simulation conditions are the same as Tab. 1. The performances of conventional IMR scheme, the proposed scheme (a) and (b) are compared. Figs. 7 to 9 show the NLOS

detection error performances of three schemes and Tab. II shows the average number of misdetection in all sensor fields.

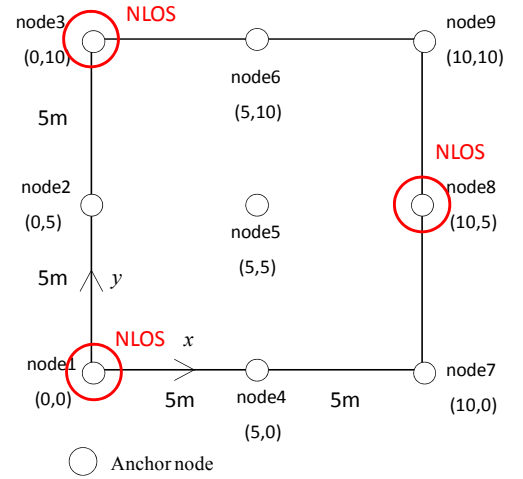


Fig. 6. Sensor field with three NLOS anchors.

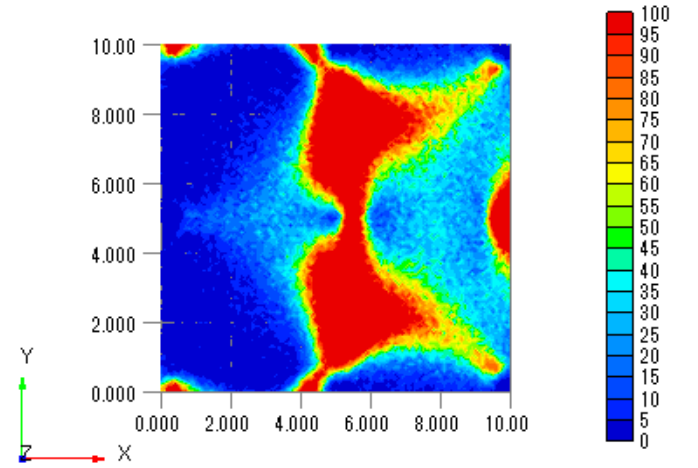


Fig. 7. NLOS detection performance of IMR scheme.

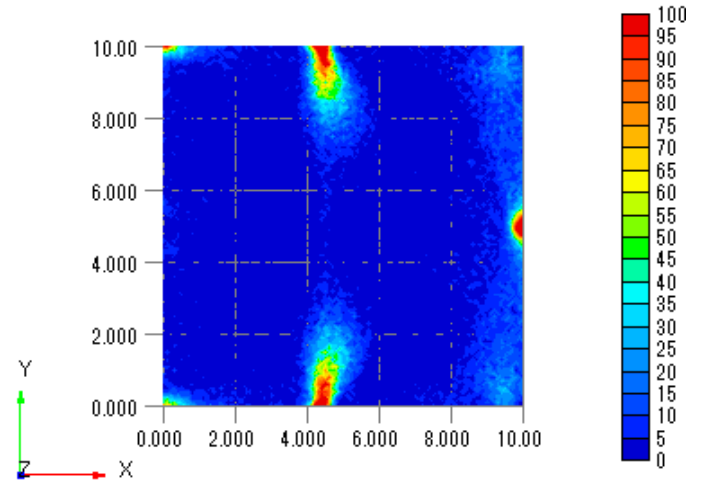


Fig. 8. NLOS detection performance of proposed scheme (a).

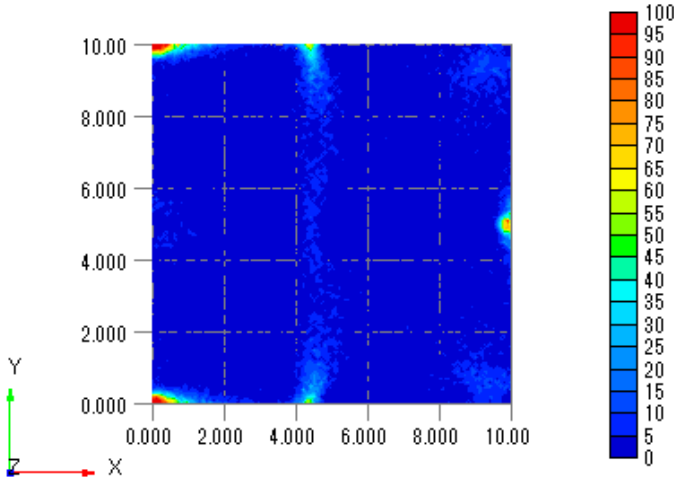


Fig. 9. NLOS detection performance of proposed scheme (b).

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

Conventional IMR	Scheme (a)	Scheme (b)
46 times	6 times	3 times

From the results, it can be seen that the IMR scheme has wider degraded area (red) as shown in Fig. 7 and that area is located at the center of sensor field because of the location of three NLOS anchor nodes as confirmed in Section V-A. In the proposed schemes of Figs. 8 and 9, the detection performance is greatly improved compared with the conventional IMR scheme, especially, 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). Although some errors remain even in scheme (b) as shown in Fig. 9 due to relatively a small number of measurements of 10, it will be improved by the measurement addition. From Tab. II we can see that the scheme (b) effectively improve the NLOS detection performance.

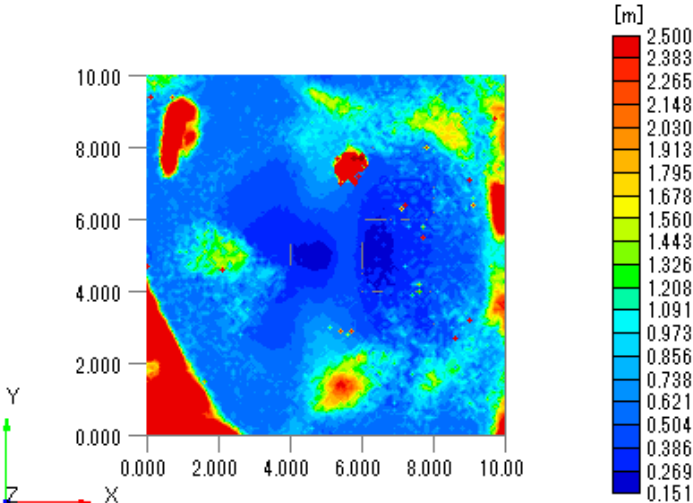


Fig. 10. RMSE performance of IMR scheme.

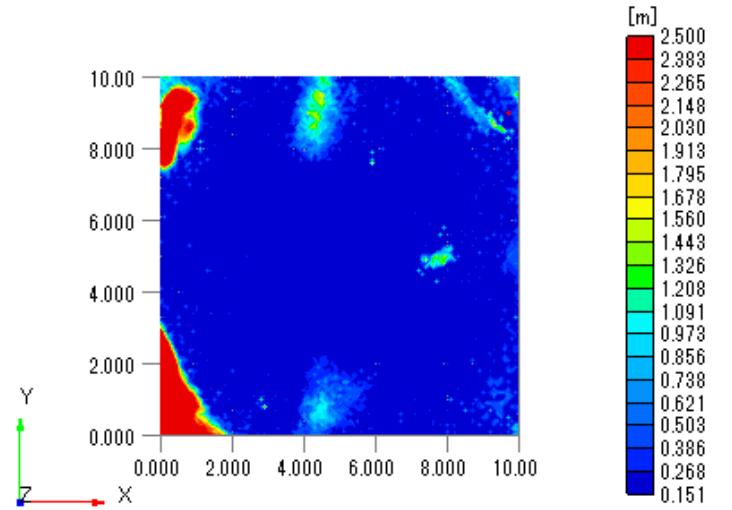


Fig. 11. RMSE performance of proposed scheme (a).

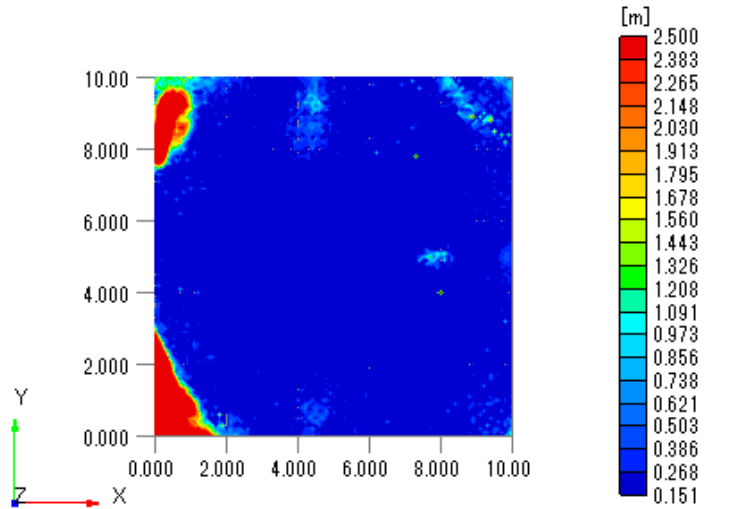


Fig. 12. RMSE performance of proposed scheme (b).

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

Conventional IMR	Scheme (a)	Scheme (b)
1.238131	0.369648	0.334711

Next, in the same simulation of Figs. 7 to 9, the RMSE performances are calculated. The results are shown in Figs. 10 to 12 and the average values of all fields are listed in Tab. III. It is shown that the proposed schemes greatly decrease the RMSE compared with the conventional IMR scheme because of the increased accuracy of the NLOS detection. However, as well as Section V-A, the RMSE performance does not directly correspond to the NLOS detection performances of Figs. 7 to 9. Especially, when comparing Figs. 7 and 10, many of the misdetection points still keep low RMSE in the LS position estimation. On the contrary, in Figs. 10 to 12 the RMSE in left lower area become worse even though the NLOS detection error is not high. These behaviors may be explained by the following two reasons. First, even if the NLOS detection error

occurs, there is a case of lowering RMSE when the sum of NLOS bias vectors is close to zero in LS estimation [1][8]. Second, in the mesh sensor field like Fig. 6, the RMSE tends to become large at the corners of the field in LS estimation [7].

Consequently, it was confirmed by the numerical analysis that the proposed LOS bias elimination scheme of (b) effectively decreases the NLOS detection error and raise the RMSE performance in TOA position estimation.

VI. 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.

In future studies, to raise the NLOS detection and RMSE performances, NLOS bias estimation function will be considered in the proposed scheme.

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