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PAPER *Special Section on Recent Progress in Antennas and Propagation in Conjunction with Main Topics of ISAP2016*

RSSI-Based Localization Using Wireless Beacon with Three-Element Array

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SUMMARY In this paper, we propose an indoor localization method that uses only the Received Signal Strength Indicator (RSSI) of signals transmitted from wireless beacons. The beacons use three-element array antennas, and the position of the receiving terminal is estimated by using multiple DOD information. Each beacon transmits four beacon signals with different directivities by feeding signals to the three-element array antennas via 180-degree and 90-degree hybrids. The correlation matrix of the propagation channels is estimated from just the strength of the signals, and the DOD is estimated from the calculated correlation matrix. For determining the location of the receiving terminal, the existence probability function is introduced. Experiments show that the proposed method attains lower position estimation error than the conventional method.

key words: *RSSI, wireless beacon, DOD estimation, localization*

1. Introduction

The satellite geolocation system called Global Navigation Satellite System (GNSS) is in wide use outdoors. However, it does not work in indoors since the satellite signals are not available. Indoor localization methods that use radio beacons have been well studied to resolve this problem [1], [2]. The radio beacons must be inexpensive, low-power consumption, easy-to-install, and capable of handling many terminals such as smartphones in crowded public spaces. Existing commercially available beacons mainly use Bluetooth-Low-Energy (BLE), however, only the RSSI of the beacon signal is available at the receiver. Most localization schemes that use RSSI [3], rely on either RSSI-ranging [4], [5] or fingerprint techniques [6], [7]. RSSI-ranging simply translates the observed RSSI into distance information by using a predetermined relationship between propagation loss and distance. The receiver estimates the distances from three or more beacons, and deduces its own location, so the locations of all beacons must be known in advance. However, it is difficult to estimate the distance accurately from just RSSI values, because multi-path fading is common in indoor environments. The fingerprint technique is known to be relatively accurate but a database of measured RSSI distributions must be created in advance for each site. The position is estimated by comparing the measured RSSI distribution with the created database. However, this method needs exhaustive measurements of the RSSI values throughout over the designated site, and a change in the propagation environment necessitates regeneration of the RSSI database. Fortunately, localization techniques based on Direction-of-Departure (DOD)/Direction-of-Arrival (DOA) information can well estimate the position of the target even when the signal strength does not correspond to the distance due to the multipath fading [8]. This approach commonly uses array antennas, and the DOD/DOA information is calculated by using array signal processing. Especially in line-of-sight environments, it can accurately estimate the position from the multiple DOD/DOA information by triangulation. Moreover, this method does not require a pre-measured database. However, the fatal problem of DOD/DOA based technique is that this technique requires phase information of the signals, which is not available in currently available beacons. The authors have studied a DOD estimation method that uses only the RSSI to solve this problem [9]. In this method, a signal pre-processing technique that uses an analog circuit is introduced for reconstructing the phase information from RSSI values. The analog feed network comprising 180-degree and 90-degree hybrids is configured at the beacon side, and the beacon signals pass through the feed network and are transmitted by a two-element array antenna. Physically speaking, the hybrids are used for forming four unique radiation patterns. The receiver observes the RSSIs of these four signals and calculates its own direction from the beacon array by using the strength differences among these signals. However, the location accuracy of this method is not sufficient because the transmitter array has only two elements. In this paper, the DOD-based localization method using three-element arrays at the beacon transmitter side [10] is experimentally investigated in detail. The accuracy of DOD estimation is improved by using the three-element array; the number of the transmitters used at each beacon, four, equals the number in our previous work [9]. Also,the estimation accuracy is improved by using the statistical approach for determining location. A measurement campaign is carried out in an actual indoor environment to evaluate the performance of the proposed method in a comparison with the RSSI-ranging method; study [10] provided only DOD-based results.

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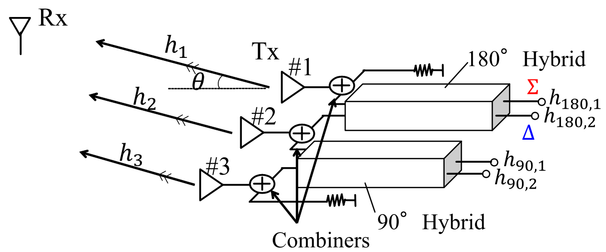


Fig. 1 Proposed system configuration.

2. Proposed RSSI-Based DOD Estimation and Localization

2.1 DOD Estimation by Using RSSI

Figure 1 shows the proposed system configuration. Four beacon signals are transmitted from the three-element array antenna connected to 180-degree and 90-degree hybrids. Transmission antennas#1 and #2 are connected to the 180 degree hybrid, while transmission antennas #2 and #3 are connected to the 90 degree hybrid. The 180 degree hybrid is used to form sum and differential patterns, and the 90 degree hybrid is used to form right- and left-direction patterns. This means four radiation patterns are created and are treated as individual beacon signals. To allow the four beacon transmitters to share the three-element array, three combiners are used to connect the feed networks to the array. One out of two input ports of the combiners at both sides of the array is terminated to keep the excitation amplitudes equal. The DOD is calculated at the receiver side by the proposed phase-reconstruction technique described below. h_1, h_2, and h_3 represent the propagation channels from the transmitting array to the receiving antenna. h_{180-1}, h_{180-2} and h_{90-1}, h_{90-2} represent the observed channel passed through the feed network and so include the characteristics of the 180-degree, 90-degree hybrids. The correlation matrix defined by the propagation channel is expressed as,

$$\boldsymbol{R} = \boldsymbol{h}^H \boldsymbol{h} = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} = \begin{pmatrix} |h_1|^2 & h_1^* h_2 & h_1^* h_3 \\ h_1 h_2^* & |h_2|^2 & h_2^* h_3 \\ h_1 h_3^* & h_2 h_3^* & |h_3|^2 \end{pmatrix} \quad (1)$$

where $\{\cdot\}^H$ and $\{\cdot\}^*$ represent complex conjugate transpose and complex conjugate, respectively. Since the channel passes through the feed network with its hybrids and the combiners, the observed channel is expressed as,

$$h_{180-1} = \frac{1}{2}(h_1 + h_2) \quad (2)$$

$$h_{180-2} = \frac{1}{2}(h_1 - h_2) \quad (3)$$

$$h_{90-1} = \frac{1}{2}(h_2 + jh_3) \quad (4)$$

$$h_{90-2} = \frac{1}{2}(jh_2 + h_3), \quad (5)$$

where the 3 dB loss of the combiners is taken into account. In this system model, the power supplied from the beacon transmitters to each input port is assumed to be identical and known. Therefore, the gain of this channel can be directly determined from the RSSI. The gain of the observed channel is represented by,

$$|h_{180-1}|^2 = \frac{1}{4}(|h_1|^2 + |h_2|^2 + h_1 h_2^* + h_1^* h_2) \quad (6)$$

$$|h_{180-2}|^2 = \frac{1}{4}(|h_1|^2 + |h_2|^2 - h_1 h_2^* - h_1^* h_2) \quad (7)$$

$$|h_{90-1}|^2 = \frac{1}{4}(|h_2|^2 + |h_3|^2 - jh_2 h_3^* + jh_2^* h_3) \quad (8)$$

$$|h_{90-2}|^2 = \frac{1}{4}(|h_2|^2 + |h_3|^2 + jh_2 h_3^* - jh_2^* h_3). \quad (9)$$

A correlation matrix can be approximated from (6)–(9) by the following procedure. Since the relation $R_{21} = R_{12}{}^*$ is satisfied, the gain difference between the sum and differential ports yields,

$$|h_{180-1}|^2 - |h_{180-2}|^2 = \frac{1}{2}(h_1 h_2^* + h_1^* h_2) = \frac{1}{2}(R_{12} + R_{21}) = |R_{12}| \cos\alpha \quad (10)$$

where α represents the phase of R_{12}. The sum of the gains is calculated as,

$$|h_{180-1}|^2 + |h_{180-2}|^2 = \frac{1}{2}(|h_1|^2 + |h_2|^2) \geq |h_1 h_2|, = |R_{12}| \quad (11)$$

where the inequality of arithmetic and geometric means is used. Note that the equality of (11) holds when and only when $|h_1|^2 = |h_2|^2$. If the transmitting array and receiving antenna are in line-of-sight (LOS), the propagating distance is sufficiently long, and the multipath component is neglected, $|h_1|^2 = |h_2|^2$ holds. Hence, α is approximated as,

$$\alpha \simeq \pm \cos^{-1}\left(\frac{|h_{180-1}|^2 - |h_{180-2}|^2}{|h_{180-1}|^2 + |h_{180-2}|^2}\right). \quad (12)$$

The approximation $|h_1|^2 \simeq |h_2|^2$ also simplifies the relation of the correlation matrix elements (1) as,

$$|R_{11}| \simeq |R_{12}| \simeq |R_{21}| \simeq |R_{22}| \simeq |h_{180-1}|^2 + |h_{180-2}|^2 = A, \quad (13)$$

where A is a real constant that is defined for simplicity. Therefore, the correlation matrix elements related to Tx #1 and #2 are approximately estimated as,

$$\begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} = \begin{pmatrix} A & Ae^{j\alpha} \\ Ae^{-j\alpha} & A \end{pmatrix} \quad (14)$$

Similarly, the correlation matrix elements involved in Tx antennas #2 and #3 are determined by the following procedure. Antennas #2 and #3 are fed through the 90-degree hybrid. From the relation of (8) and (9), the gain difference between the 90-degree hybrid ports, h_{90-1} and h_{90-2}, yields,

$$|h_{90-1}|^2 - |h_{90-2}|^2 = \frac{1}{2}(-jh_2h_3^* + jh_2^*h_3) = \frac{1}{2}(jR_{23} - jR_{32}) = -|R_{23}|\sin\beta \quad (15)$$

where β represents the phase of R_{23}. The sum of the gains is calculated as,

$$|h_{90-1}|^2 + |h_{90-2}|^2 = \frac{1}{2}(|h_2|^2 + |h_3|^2) \geq |h_2h_3| = |R_{23}|. \quad (16)$$

As in (11), the approximation, $|h_2|^2 = |h_3|^2$, yields $|h_{90-1}|^2 + |h_{90-2}|^2 \simeq |R_{23}|$, which leads to

$$\beta \simeq \sin^{-1}\left(-\frac{|h_{90-1}|^2 - |h_{90-2}|^2}{|h_{90-1}|^2 + |h_{90-2}|^2}\right), \quad \pi - \sin^{-1}\left(-\frac{|h_{90-1}|^2 - |h_{90-2}|^2}{|h_{90-1}|^2 + |h_{90-2}|^2}\right). \quad (17)$$

Also, the correlation matrix elements related to Tx #2 and #3 satisfy the relation of,

$$|R_{22}| \simeq |R_{23}| \simeq |R_{32}| \simeq |R_{33}| \simeq |h_{90-1}|^2 + |h_{90-2}|^2 = B, \quad (18)$$

where B is a real constant, too. Therefore, the correlation matrix elements related to Tx #2 and #3 are approximated as,

$$\begin{pmatrix} R_{22} & R_{23} \\ R_{32} & R_{33} \end{pmatrix} = \begin{pmatrix} B & Be^{j\beta} \\ Be^{-j\beta} & B \end{pmatrix}. \quad (19)$$

As discussed above, each of the angles, α and β, has two solutions, where only one of the two is true. Note that $h_1h_2^* = h_2h_3^*$ holds in the ideal environment, where only a single plane wave exists and there is no multipath component. By considering (1), α and β represent the phase difference between the paths of the adjacent antennas, and they should, in theory, be identical. Therefore, the true solutions of α and β will agree whereas the false solutions do not. Hence, the selection method is quite simple, and consists of just choosing the set of α and β with the smallest difference. Component R_{13} physically represents the signal correlation between the transmitting antennas, #1 and #3, and can be approximated as,

$$R_{13} \simeq |R_{23}|e^{j(\alpha+\beta)} = \frac{R_{12}R_{23}}{R_{11}} = \frac{ABe^{j(\alpha+\beta)}}{A} = Be^{j(\alpha+\beta)} \quad (20)$$

where the relation, $|h_1| \simeq |h_2| \simeq |h_3|$ is assumed. Thus, all elements of the correlation matrix can be derived from just the strength information. The estimated correlation matrix is expressed as,

$$\boldsymbol{R} = \begin{pmatrix} A & Ae^{j\alpha} & Be^{j(\alpha+\beta)} \\ Ae^{-j\alpha} & A & Be^{j\beta} \\ Be^{-j(\alpha+\beta)} & Be^{-j\beta} & B \end{pmatrix} \quad (21)$$

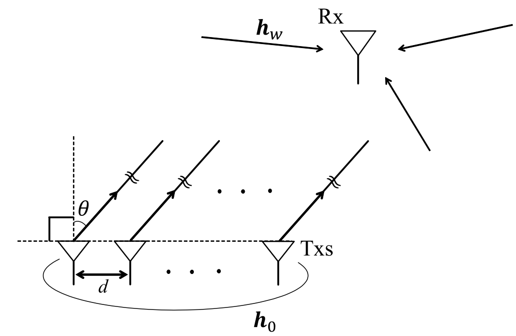


Fig. 2 Simulation model.

Subsequently, DOD can be easily calculated by any of the commonly used algorithms, such as MUSIC (MUltiple SIgnal Classification) method[11]. We simulated a simple model in order to clarify the performance of the proposed method. The simulation results clarified the performance improvement over the two-element array. We also compared the performance with an ideal three-element array, i.e. DOD with phase information. Figure 2 shows the model simulated. In this figure, Txs represent an M-element transmitting linear antenna, and Rx represents a one-element receiving antenna that is placed sufficiently far from the Txs; θ is the angle of signal transmission, and d is the distance between antenna elements. All the antenna elements were assumed to be ideal point wave sources (i.e. omni-directional). The channel vector of propagation is written as,

$$\boldsymbol{h} = \boldsymbol{h}_0 + \boldsymbol{h}_w, \quad (22)$$

where $\boldsymbol{h}_0$ is LOS (Line-Of-Sight) component, which is represented as,

$$\boldsymbol{h}_0 = \frac{h_0}{\sqrt{M}}[1, e^{jkd\sin\theta}, \ldots, e^{jkd(M-1)\sin\theta}], \quad (23)$$

where h_0 represents the coefficient of strength of the channel vector, and k represents the wave number. $\boldsymbol{h}_w$ represents the NLOS (Non-Line-Of-Sight) component, each element of which is assumed to be a random complex vector following a Gaussian distribution. The Rician factor was calculated from $k = \frac{|\boldsymbol{h}_0|^2}{|\boldsymbol{h}_w|^2}$. From the vector channel and (1), the correlation matrix is written as,

$$\boldsymbol{R} = \boldsymbol{h}^H\boldsymbol{h}. \quad (24)$$

We then evaluated the angular estimation error achieved with the MUSIC method. In this simulation, the value of θ is assumed to be −45°–45°,and d is set to a half-wave length, the Rician factor is $k = 10$, and the number of trials is 10000. Figure 3 shows the CDF (Cumulative-Distribution-Function) of the angular estimation error yielded by the simulation. In this figure, w/ phase represents the results of two-element and three-element arrays with knowledge of phase information. From this figure, we find that proposed ($M = 3$) is lower accuracy than w/ phase ($M = 3$), but proposed ($M = 3$) has higher accuracy than the two-element array. This result shows the proposed method offers better accuracy than w/

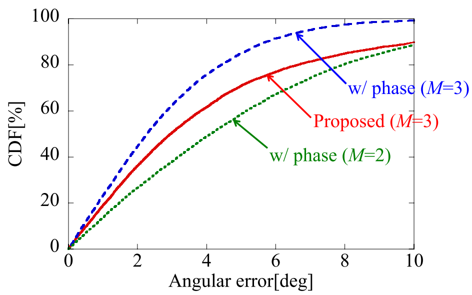


Fig. 3 CDF of angular error (simulation).

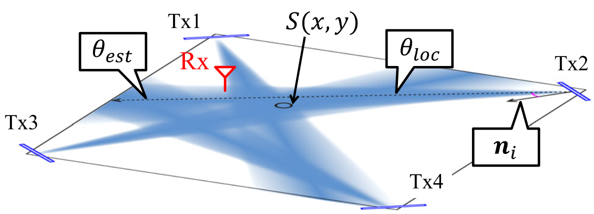


Fig. 4 Concept of proposed localization method.

phase ($M = 2$) does even though the phase information is not used.

2.2 Localization by Using Only RSSI

This study introduces an angular probability function, the Gaussian function; its maximum is taken to the estimated DOD. By taking all probabilities into consideration, the location most likely to be true is identified. Figure 4 shows the concept of the proposed localization method. In this figure, $\boldsymbol{n}_i$ represents a normal vector of the i-th array antenna, and θ_{loc} and θ_{est} represent direction from transmitting antenna Tx #i to point $S(x, y)$ and DOD calculated by the correlation matrix, respectively. The existence probability, f_i, at point $S(x, y)$ for Tx #i is defined as,

$$f_i(\boldsymbol{r}_{ST_i}, \theta_{est}) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\theta_{\mathrm{loc}}(\boldsymbol{r}_{\mathrm{ST_i}}) - \theta_{\mathrm{est}})^2}{2\sigma^2}\right) \quad (25)$$

where $\boldsymbol{r}_{ST_i}$ is the direction vector from Tx #i to point $S(x, y)$, and σ^2 represents the variance of the Gaussian function. The value of σ^2 is arbitrarily set, because we confirmed that there is no significant change in accuracy when the value of σ^2 is changed. The probabilities yielded by all Txs are given as,

$$F(r_{ST_i}) = \prod_{i=1}^{N} f(r_{ST_i}) \quad (26)$$

where N is the number of Txs. The position at which the existence probability is maximum in the estimated range is identified. Therefore, this proposed method is robust even of some of the DOD estimations fail. Figure 5 shows the flowchart of the proposed localization method. In the flowchart, 'Correlation matrix estimation' represents calculation of the correlation matrix shown in (1)–(21) at Rx.

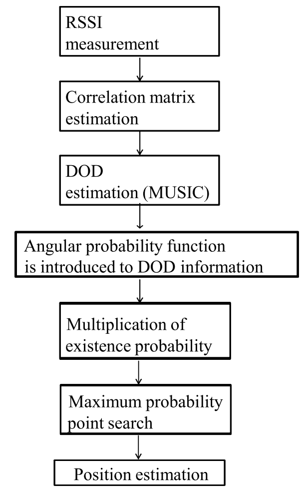


Fig. 5 Flowchart of proposed localization method.

'DOD estimation (MUSIC)' represents the angular estimation by applying the MUSIC method to the estimated correlation matrix. 'Angular probability function is introduced to DOD information' represents the application of the angular probability function as shown in (25). 'Multiplication of existence probability' represents the multiplication of existence probability as shown in (26). Finally, 'Maximum probability point search' represents the search of the position of maximum existence probability in the estimation range. Note that the proposed method assumes the locations and orientations of all Txs are known in advance.

3. Experimental Conditions and Environment

Figure 6 shows the experimental environment, and Fig. 7 shows the experimental setup. This experiment was carried out in an indoor environment, the size of which was 14 m × 10 m; the operating frequency lay in the 2.4 GHz band. It is obvious that this environment is multipath because it is surrounded by concrete walls [12], [13]. The transmitting arrays were placed at the four corners of the test area, and directed at the angle of 45° with respect to the walls. Measurements were made at 65 locations (receiving antenna), as shown in Fig. 6. Figure 8 shows the antennas used in this experiment, and Fig. 9 shows their measured directivities. The sleeve antenna and the patch antennas were designed with a center frequency of 2.47125 GHz. The sleeve antenna was used at the receiving side. Each transmitting array consisted of three-element patch antennas, where the inter-element spacing was one half the wavelength of 2.47125 GHz. Antenna height was 1.0 m. In the measurement regime, all Tx antennas were alternately fed through an RF switch, and complex channels between the Rx antenna and all Tx antennas were measured. RSSI values were determined by multiplying the absolute value of the complex channel by the assumed transmission power. We did not use an actual hybrid circuit in this experiment, and only a basic evaluation of the proposed method was attempted. Hence, we post-processed

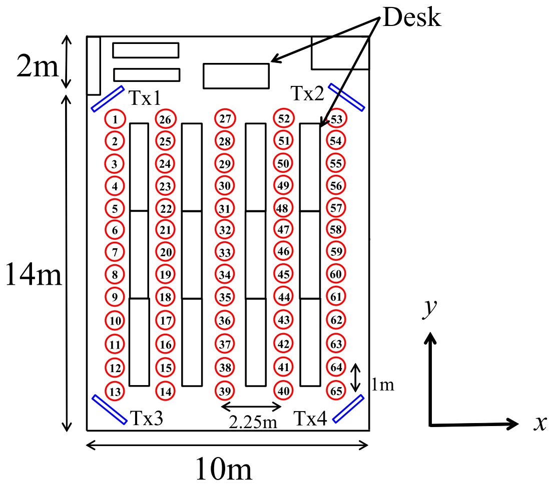


Fig. 6 Experimental environment.

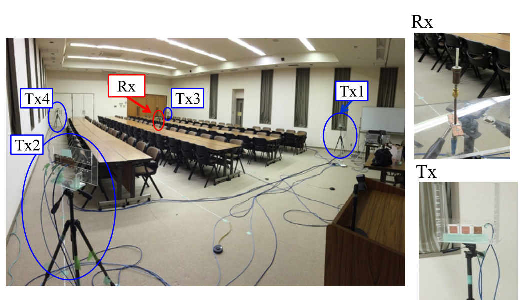
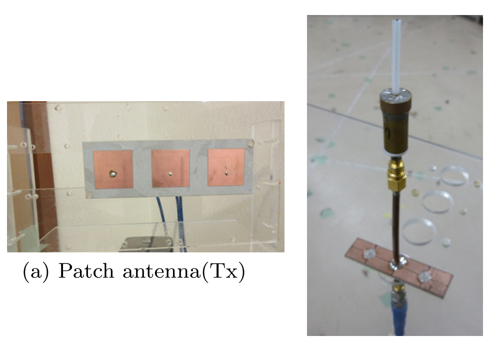


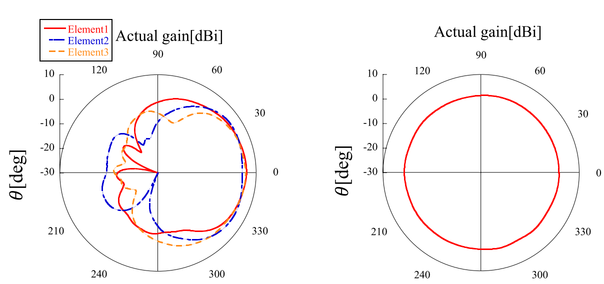
Fig. 7 Experimental setup.



(a) Patch antenna(Tx)

(b) Sleeve antenna(Rx)

Fig. 8 Photos of Tx and Rx antennas.



(a) Patch antenna

(b) Sleeve antenna

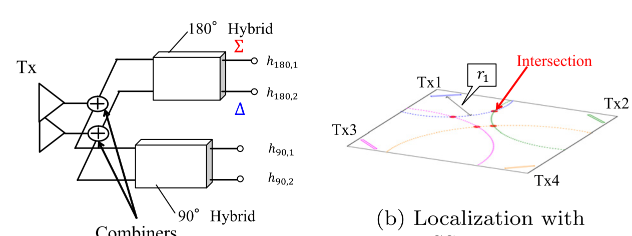
Fig. 9 Directivities of antennas used.

the gathered data. First, we measured the complex channel between the feed port of the antenna and the receiving antenna. Second, the channel through the feed network using ideal hybrids was estimated using by the cascade connection technique using S-parameter [14].

4. Measurement Results

Four other localization methods were used in assessing the performance of the proposed method. One was the DOD-based localization method; an enhancement of the method of reference [9], that uses the likely-hood approach described in Sect. 2.2, and a 90-degree hybrid is used in addition to the 180-degree hybrid. Figure 10(a) shows the concept of this method with two antenna elements. Four beacon signals are transmitted by the two antenna elements by passing the signal through 90-degree and 180-degree hybrids. The output signals from the two hybrids are combined just before the antenna feed ports. In addition, the DOD-based localization method using two-element array and three-element array with phase information were used to compare the performance of proposed localization. And also, a likely-hood approach described in Sect. 2.2 is introduced to these localizations with phase information. The MUSIC algorithm was used to estimate the DODs in the proposed and conventional DOD-based methods. The other method used the RSSI-ranging algorithm. Figure 10(b) shows the concept of localization by translating RSSI to distance. The circles indicate the estimated distances, and the receiver position should be lie the intersection of the circles. However, the intersection points are not precise due to distance estimation error. In this study, location is estimated by averaging all intersection points.

Figure 11 shows the distributions of the RSSI corresponding to the four Txs. It can be seen that the RSSI attenuates with distance from Tx, but the degree of the attenuation strongly depends on the direction from Tx. Figure 12 plots the relation between propagation distance and RSSI, which is calculated from the received power and the distance between receiving antenna and transmitting antennas in the environment see Fig. 6. Figure 12 shows the relation between RSSI and propagation distance, D, which is the distance between the transmitting and receiving antennas. Figure 12 shows that the received power falls as the distance increases. The position is estimated by averaging all locations of the in-



(a) 2-element DOD beacon

(b) Localization with RSSI-ranging

Fig. 10 Concept of conventional localization.

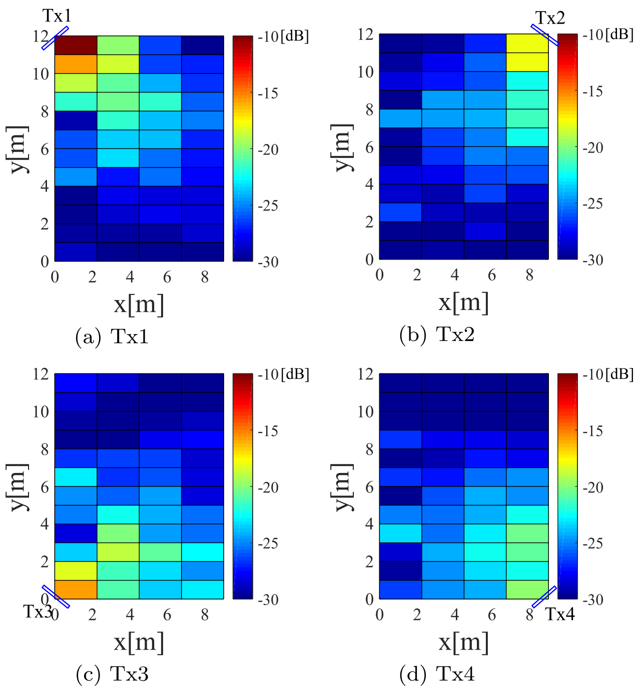


Fig. 11 RSSI distributions with four Txs.

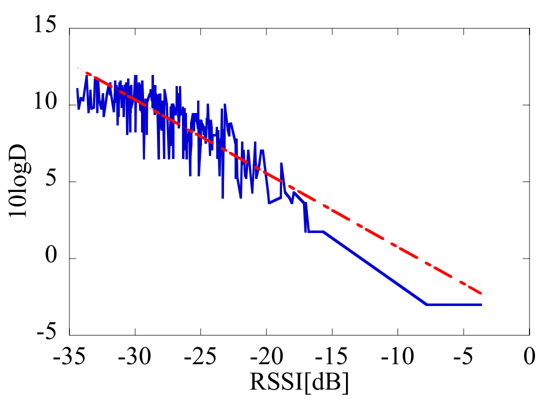


Fig. 12 Received signal power vs propagation distance.

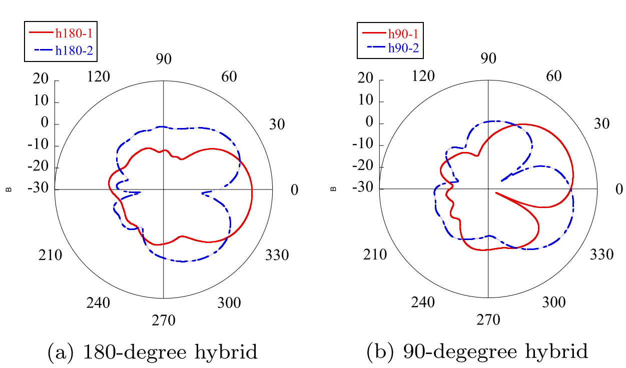


Fig. 13 Directivities of antennas used with circuit.

tersections within the estimation range. Figure 13 shows the four antenna directivities of used antennas with the proposed circuit. We calculated four antenna radiation patterns by ap-

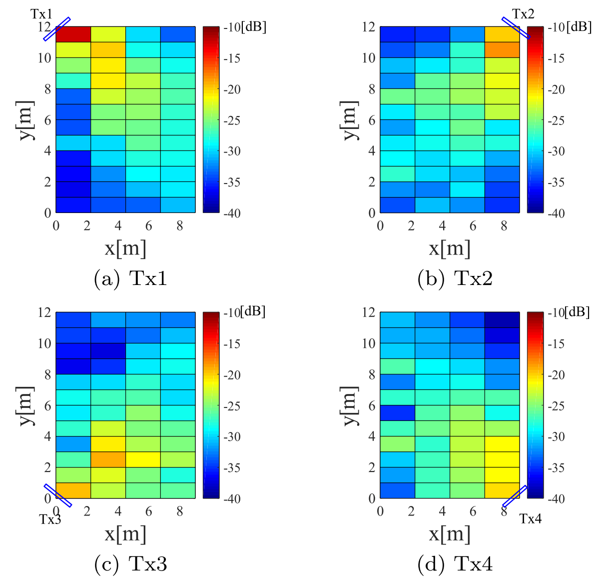


Fig. 14 RSSI distributions with four Txs (h_{180-1}).

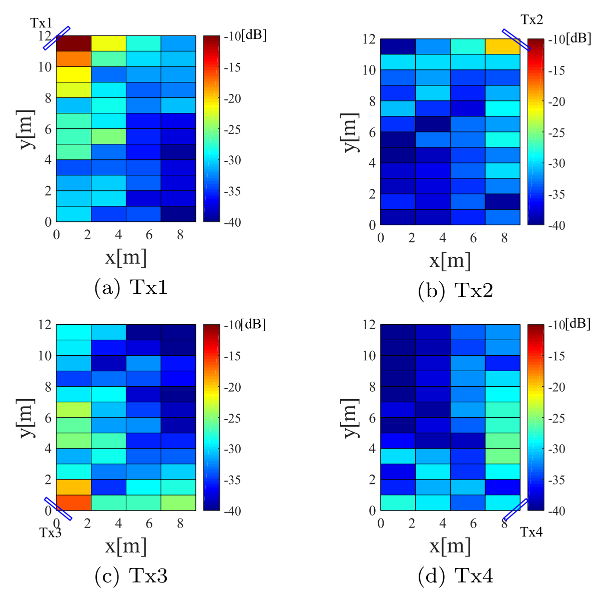


Fig. 15 RSSI distributions with four Txs (h_{180-2}).

plying the weight generated by the ideal proposed circuit to the measured antenna patterns. Figure 14–17 shows the distribution of the RSSI of the proposed method, where four distributions are depicted for each beacon location because four different signals are transmitted with four radiation patterns. From these figure, it can be seen that the proposed feed network transmits signals with four different antenna directivities. Figure 18 evaluates the angular estimation error with respect to amplitude difference. This figure shows how much the angular estimation error is affected by the amplitude difference between elements due to multipath fading; amplitude difference between elements is calculated as the variance (σ_a^2). From figure, it can be seen that the angular estimation error increases with variance, and we confirmed

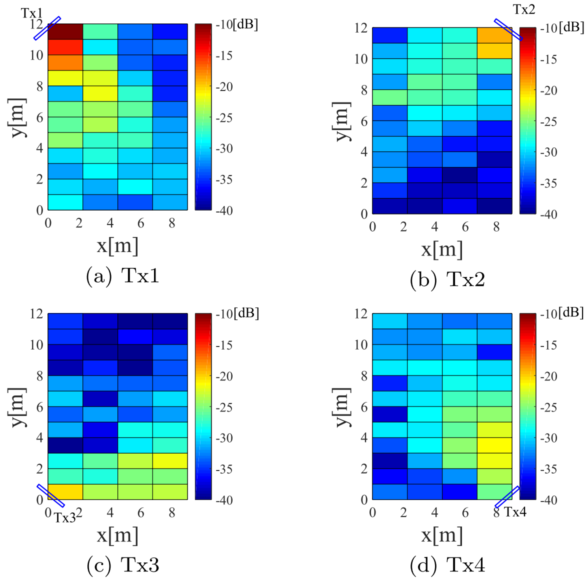


Fig. 16 RSSI distributions with four Txs (h_{90-1}).

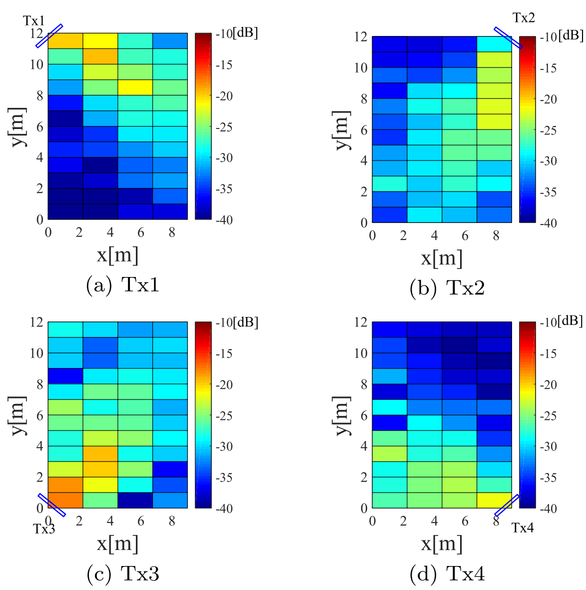


Fig. 17 RSSI distributions with four Txs (h_{90-2}).

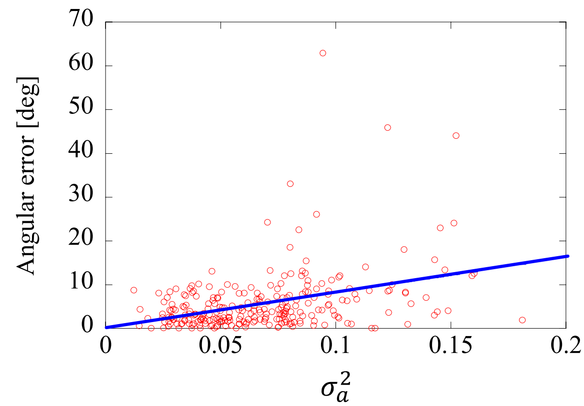


Fig. 18 Evaluation of angular estimation error vs amplitude difference.

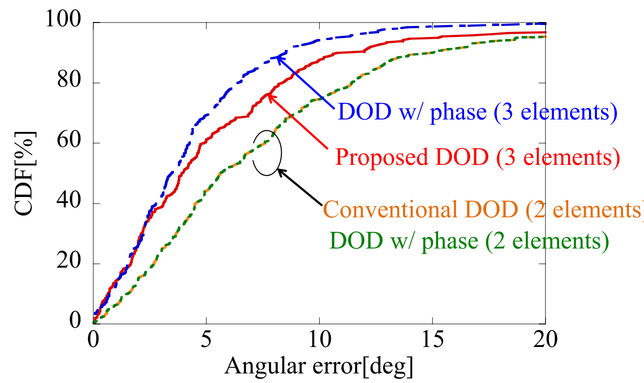


Fig. 19 CDF of angular error.

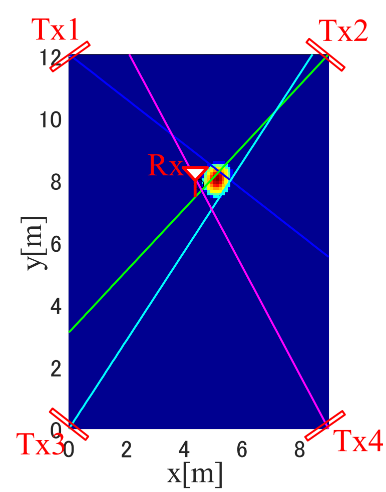


Fig. 20 Example of proposed localization.

that the 90 percentile value of angular estimation error does not exceed 8.90 degrees. Figure 19 shows CDF of the angular errors of the direction estimates. The proposed method was compared to the conventional method, i.e. the DOD estimation technique using two-element array antennas that shown in Fig. 10(a). The proposed method is also compared to the DOD estimation techniques, where two-element methods with and without phase information and three-element method with phase information are used. The measured tendency well agrees with the simulation results shown in Fig. 3. The 50 percentile values of the error in the proposed method and the three-element array method using phase information were 3.9°, 3.5°, respectively. And, the 50 percentile values of the error in both of the conventional two-element array method shown in Fig. 10(a) and the two-element array method using phase information were 5.6°. Although the proposed method is lower accuracy than the three-element array with phase information, it is found that the proposed method improves the DOD estimation error by 1.7° compared to the conventional two-element method. Figure 20 shows the probability distribution calculated from the measured RSSI by using (26), where the Rx is located at point

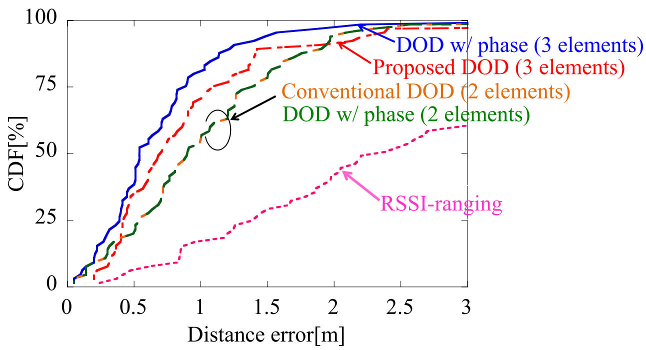


Fig. 21 CDF of distance error.

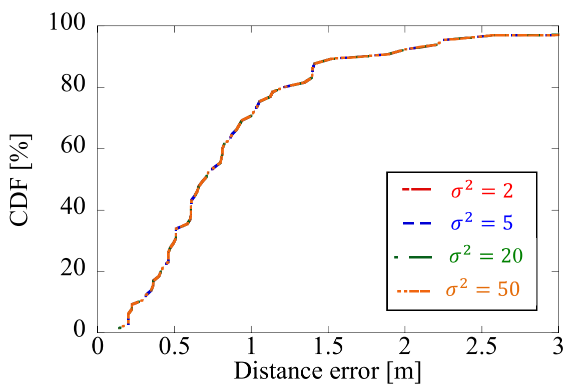


Fig. 22 CDF of distance error for various σ^2 values.

31, i.e. $(X, Y) = (4.5, 8.5)$. The lines indicate the DOAs estimated by the proposed method. Even though some of the esitimated DODs have slight angular error, the probability maximum appears around the actual location. The distance between the maximum point and actual location is 0.63 m in this case. Figure 21 shows CDF of the distance errors of the position estimates. In addition to the DOD-based methods, the localization result of the RSSI-ranging-based technique is also plotted. From this figure, it can be seen that it is difficult to estimate the position by the RSSI-ranging method since the RSSI is not directly proportional to distance as shown in Fig. 12. This yields several false images and thus large error in localization. Also, the proposed method was compared to the conventional method, i.e. the DOD estimation technique that uses two-element array antennas that shown in Fig. 10(a). In addition, it was compared to the DOD estimation technique using two-element array and three-element array with phase information. The 50 percentile values of the error in the proposed method and the three-element array method using phase information were 0.7 m, 0.5 m, respectively. And, the 50 percentile values of the error in both of the conventional two-element array method shown in Fig. 10(a) and the two-element array method using phase information were equally 0.9 m. Although the proposed method is lower accuracy than the three-element array with phase information, it is found that the proposed method improves the position estimation error by 0.2 m compared to the conventional method. Figure 22 shows the CDF of the distance error in the estimated position when the value of σ^2 in (25) was varied. Figure 22 shows that the estimation performance is constant regardless of σ^2. These results confirm that the proposal to use three-element array antennas offers highly accurate localization even in multipath indoor environments.

5. Conclusion

This paper has proposed an improved indoor localization method that uses the DOD information calculated from the RSSI values of signals transmitted from three-element array antennas. This method uses multiple beacon signals, each of which are generated from three-element antennas connected to four beacon transmitters by way of 180-degree and 90-degree hybrids. Experiments showed that the proposed DOD estimation method improves the median angular error by 1.7° compared to the conventional method. Moreover, the accuracy of the proposed method with three-element array was 0.7 m (50 percentile), whereas the accuracies of the two-element method and RSSI-ranging-based method were 0.9 m and 2.7 m, respectively (50 percentile). These results indicate that the proposed method with three-element arrays at the beacon side offers the best accuracy among the methods examined in this study. We are currently studying the use of actual hybrid circuits, and the accuracy of the position estimates yielded with actual circuits will be announced in a future paper.

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