An Error Reduction Algorithm for Position Estimation Systems Using Transmitted Directivity Information

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***Abstract*—We consider a position estimation system for targets that exist in near wide area. The system has multiple sensors and estimates position using multiple receivers. Previously, receivers arranged in a straight line would generate a large position error in the direction of the line. In order to reduce this error, we herein propose a novel estimation algorithm using the directivity information of the transmitter. The proposed system uses the directional emission of an array of antennas in a transmitter. In the present paper, the error characteristic to be solved is introduced. The proposed algorithm is then presented. Finally, the error reduction performance is demonstrated through computer simulations. The obtained results indicate good error reduction performance.**

***Keywords*-sensor network; position estimation; localization; radar network; directivity**

I. INTRODUCTION

Interest in position estimation systems has been growing. In this paper, we focus on the estimation of the position of targets in the near wide area. Our position estimation systems are built with multiple sensors that are connected with networks (Figure 1). These sensors achieve reliable detection and accurate position estimation. Good performance can be achieved using even inexpensive devices. Moreover, networked sensors can cover a wide detection area. Several attractive applications of position estimation systems have been suggested, including indoor monitoring systems and near-range automotive radars [1], [2].

We assume that the sensors in the network can output only measured ranges (a measured range list) to the targets because of low cost and the simplicity of the components used to construct the sensors. The estimator must calculate target positions with high accuracy from only measured range lists provided by multiple sensors. For accurate positioning, it is important to discuss data processing of position estimation, which deals with measured range data from all of the sensors.

Over the past few years, several algorithms have been developed for position estimation using multiple sensors. As related work with multiple sensing devices, several studies have been made on sensor network systems [3]–[7]. Radar network systems have also been proposed [8]–[10]. Based on previous studies, trilateration techniques using geometric operations are popular for estimating target positions. These techniques are not optimum in terms of accuracy with respect to position estimation and may also detect "ghost targets", which are falsely detected about non-existent targets. This often occurs when the measured errors are large [1], [10].

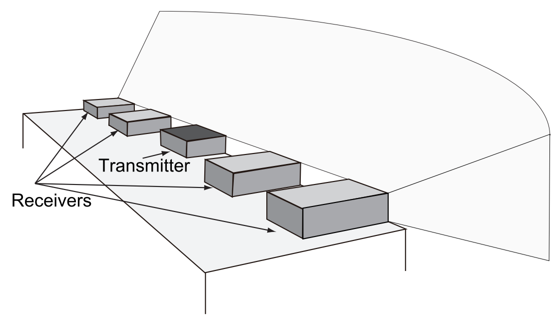

Figure 1. Position estimation system

In other techniques, measured ranges are treated as stochastic variables [11]–[13]. Typical techniques include estimation using minimum mean square error (MMSE) and maximum a posterior probability (MAP). The accuracy of these techniques is high compared to basic trilateration techniques. However, applying the MMSE method to the estimation of multiple targets is not easy. Among stochastic methods, the accuracy of the MAP method is optimum. However, data processing in the MAP method is complex. Therefore, we proposed a novel estimation algorithm, namely, the existence probability estimation method (EPEM). The EPEM calculates the existence probability of targets and estimates the target positions [14]. In the proposed method, the measured ranges are also treated as stochastic values. Moreover, the proposed method has approximately the same estimation accuracy and a lower

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calculation burden compared to MAP methods.

However, the estimation errors depend on the layout of the receivers. In particular, for the case in which the receivers are arranged in a straight line, large errors are generated in the direction of the line. Usually, a straight-line arrangement is useful because such an arrangement is easy to build and can be set up within a limited space. Thus, a technique to reduce the estimation errors is needed.

The goals of the present paper are as follows:

- Introduction of the EPEM algorithm,
- Clarification of the error performance depending on the sensor arrangement and description of the problem,
- Proposal of the existence probability estimation method with directivity information (EPEMD) algorithm,
- Evaluation of the error reduction through computer simulations.

The existence probability of the EPEMD is calculated using the directivity information of a cooperative transmitter. In the case of radar network systems, transmitters often use a directivity scan in order to reduce misdetections and expand detectable ranges for a limited power [15]. In the case of sensor network systems, the construction of electrical directivity antennas is advantageous because the sensor device requires a long deliverable range with low power. Therefore, it is meaningful to propose an estimation algorithm that considers the directivity pattern. As such, we evaluate the error reduction through computer simulations.

The remainder of this paper is organized as follows. In Section II, we present the system model and assumptions of the present study. In Section III, we introduce the EPEM algorithm, which is a position estimation algorithm. The algorithm is explained analytically, and the error performance and problems are presented. In Section IV, the proposed EPEMD algorithm is presented. In Section V, the performance of the error reduction is evaluated. Finally, Section VI summarizes the present study and presents suggestions for further research.

II. System model of the position estimation system

We consider an estimation system with a transmitter and multiple receivers (Figure 1). Figure 2 and 3 show the system model. Figure 2 shows the sensor layout and the targets for position estimation. The numbers of receivers and targets are K and N, respectively. The origin of the coordinate system is the center of the receivers. The target position is given as (x_n, y_n), $1 \leq n \leq N$. Each receiver is assumed to be located on the x-axis. The x positions of the receivers are $\alpha_1, \alpha_2, \alpha_3, \cdots, \alpha_K$.

The kth receiver outputs a measured range list composed of the ranges, namely, $\tilde{R}_k = (\tilde{r}_{k1}, \tilde{r}_{k2}, ..., \tilde{r}_{kN_k})$. Here, $N_k (\leq N)$ is the number of ranges included in the measured range list $\tilde{R}_k$. We assume the existence of a only direct path between target and transmitter/receiver. Subscript ($\tilde{}$) indicates measured values.

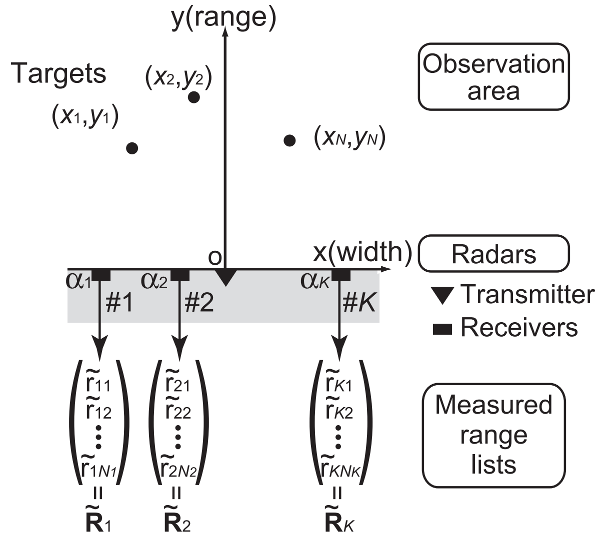

Figure 2. Layout of sensors and targets

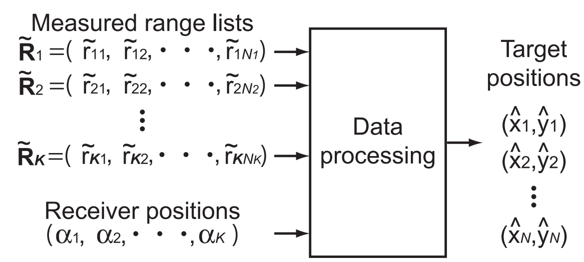

Figure 3. A data flow

Each measured range $\tilde{r}_{kn}$ in the list includes a measurement error:

$$\tilde{r}_{kn} = r_{kn} + \epsilon_k, \tag{1}$$

where r_{kn} is the true range between the nth target and the transmitter / the kth receiver, and ϵ_k is a stochastic variable, the variance of which is denoted as σ_k^2. Using the measured range lists obtained from all receivers and the position of the receivers, the target positions are estimated as shown in Figure 3.

III. Estimation algorithm

In this section, we first introduce the proposed position estimation algorithm using the existence probability. The estimation characteristics are then summarized, and the problem is described.

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A. Existence probability estimation method (EPEM)

Commonly used trilateration methods have a number of problems, as mentioned in Section I. In order to address these problems, the proposed estimation method, which is described below, deals with the measured rages as stochastic variables.

In order to estimate the target positions using the measured range lists provided by the receivers, we consider the following existence probability, which includes the conditional probability:

$$P(\hat{x},\hat{y}|\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K). \quad (2)$$

The probability of Equation (2) is the conditional probability of the target existence at $(\hat{x},\hat{y})$ when the measured range lists $\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K$ are obtained. Using Bayes' theorem, Equation (2) may be written as follows:

$$\frac{P(\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K|\hat{x},\hat{y})}{P(\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K)}\cdot P(\hat{x},\hat{y}). \quad (3)$$

In Equation (3), the denominator does not depend on the estimated parameter $(\hat{x},\hat{y})$. Therefore, when $P(\hat{x},\hat{y})$ is distributed uniformly, Equation (3) may have the same distribution shape:

$$P(\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K|\hat{x},\hat{y}). \quad (4)$$

Each receiver is independent. Equation (4) may be expressed as follows because the measured range is an independent Gaussian variable:

$$\prod_{k=1}^{K} P(\tilde{R}_k|\hat{x},\hat{y}). \quad (5)$$

Considering the combinations of targets and ranges, Equation (5) may be expressed as follows:

$$\prod_{k=1}^{K}\sum_{n=1}^{N} P(\tilde{r}_{kn}|\hat{x},\hat{y}) \quad (6)$$

where we assume no pre-knowledge of the targets. In other words, the receivers do not know the relationship between the targets and the measured ranges. Next, the estimated parameters $(\hat{x},\hat{y})$ can be transformed with the range from the transmitter/kth receiver to the target, i.e., $\hat{r}_{kn}$ as follows:

$$\hat{r}_{kn} = \sqrt{(\hat{x}-\alpha_k)^2+\hat{y}^2}+\hat{x}^2+\hat{y}^2 \quad \text{(for all } n). \quad (7)$$

Using the above relationship, Equation (6) is transformed into the following:

$$\prod_{k=1}^{K}\sum_{n=1}^{N} P(\tilde{r}_{kn}|\hat{r}_k). \quad (8)$$

The probability of $P(\tilde{r}|\hat{r})$ indicates the error characteristic of the known receiver. Using Equations (7) and (8), the distribution of the probability of the target existence at position $(\hat{x},\hat{y})$ can be calculated when the measured ranges $\tilde{R}_1,\tilde{R}_2,\tilde{R}_3,\cdots,\tilde{R}_K$ are obtained. By selecting the local maximums of the distribution of Equation (8), the target positions can be estimated. The EPEM has approximately the same estimation accuracy as the MAP method, which is optimum in terms of maximum a posteriori probability [14].

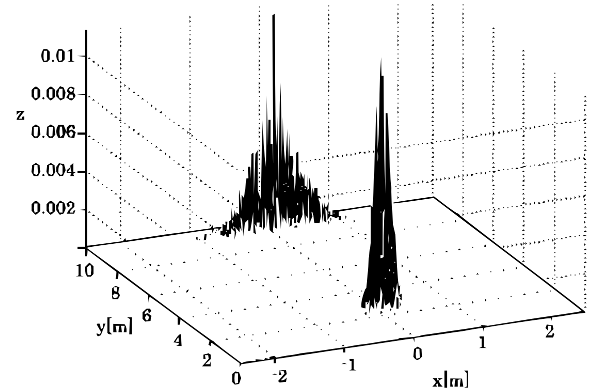

Figure 4. Distribution of estimated target positions (EPEM)

Table I
SIMULATION PARAMETERS 1

Number of receivers: K	3
Number of targets: N	2
Target positions	#1 $(x_1,y_1)=(0,2)[m]$ #2 $(x_2,y_2)=(0,9)[m]$
Array width of receivers	2 m
Distribution of measurement error $\tilde{r}$	Gaussian distribution ($\sigma_k = 0.075$)
Number of iterations	20,000

B. Estimation characteristics and problems

In the following, we present the estimation characteristics of the EPEM algorithm described in the previous section. The simulation parameters are shown in Table I. In the simulations, we assume the measurement error to be 0.3 m, which is typical [16]. According to this value, we set the standard derivation σ_k of the measured ranges ($4\sigma_k = 0.3$ [m]). The estimation trials of the targets are simulated. The trials generate the distribution of estimated positions. The results are shown in Figure 4. Moreover, the mean and variance of the distribution for each target position in Figure 4 are summarized in Table II. Figure 4 and Table II show that the error in the x-direction is larger than that in the y-direction. The reason for this is that the receivers are arranged along the x-axis. That is, large errors are generated in the direction of the receivers. In order to reduce the x-axis errors, we propose an estimation algorithm that uses the directivity of the transmitter.

IV. ESTIMATION ALGORITHM USING THE DIRECTIVITY OF THE TRANSMITTER

In this section, we first propose the estimation algorithm to solve the problem of the large error described in the pre-

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Table II
CHARACTERISTICS OF THE ESTIMATED TARGETS (EPEM)

	Target 1	Target 2
E[$\hat{x}$] [m]	-0.001	-0.022
Var[$\hat{x}$]	0.014	0.240
E[$\hat{y}$] [m]	1.997	8.987
Var[$\hat{y}$]	0.002	0.002

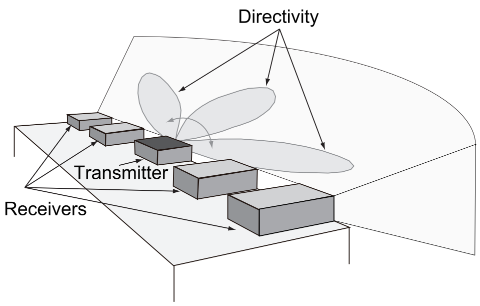

Figure 5. Image of the proposed system

vious section. The proposed algorithm is named as EPEMD (the existence probability estimation method with directivity information). Figure 5 shows an image of the proposed system. The difference between Figure 1 and Figure 5 is that the transmitter of Figure 5 has directivity.

A signal is radiated from the transmitter, which is composed of two or more antennas to achieve directivity. The reflected signal from the target is received by the receivers, which are placed along a straight line (x-axis). We introduce a transmission array antenna composed of L antennas, as shown in Figure 6. The antennas, which are centered at the origin of the coordinate system, are arranged symmetrically. The positions of the transmission antennas are assumed to be $(\beta_1, 0), (\beta_2, 0), \ldots, (\beta_L, 0)$. The variables A_l and $s_l(t)$ indicate the amplitude coefficient and the radiated signal from the lth antenna, respectively. The total signal in the θ direction is as follows:

$$S_{\text{sum}}(\theta, t) = s(\theta, t) \sum_{l=1}^{L} A_l \exp\{j2\pi f_0 (\frac{\beta_l}{c} \sin\theta)\} \quad (9)$$

where f_0 is the center frequency of the signal, and c is the speed of light. The based signal and common characteristic of the antennas, such as the directivity pattern of the element, is substituted as $s(\theta, t)$. In the present study, $|S_{\text{sum}}(\theta, t)|$, which indicates the gain generated by the array, is named as the directivity response pattern.

We attempt to reduce the estimated errors using this directivity response pattern. An example of a directivity response pattern is shown in Figure 7. Given this directivity response pattern, the signal can be reflected only from obstacles that exist in the area within the beam, such as Target #1. In contrast, Target #2 does not reflect the signal.

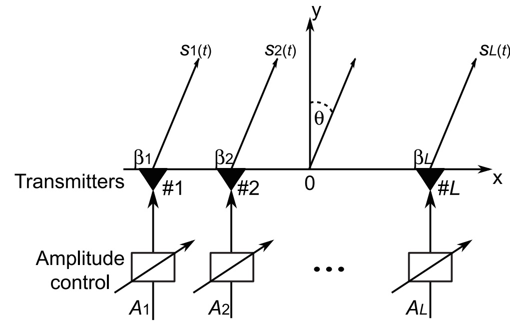

Figure 6. Structure of the transmitter

The function to specify the detectable area is as follows:

$$D_p(x, y) = \begin{cases} 1 & \text{(area that can be detected)} \\ 0 & \text{(area that cannot be detected)} \end{cases} . \quad (10)$$

Equation (10) expresses the area in which the target can reflect the signals or not. The reflectable area of the x-y plane can be calculated from the directivity response pattern.

The directivity response pattern is converted to the reflectable area of the x-y plane using the following radar equation:

$$S = \frac{\gamma P_t}{R^4} \quad (11)$$

where S is the electric power of the reflected signal, i.e., the signal received at the receiver, and γ is determined on the basis of, for example, the antenna gain and the effective reflection area of the targets. In addition, P_t is the power of the transmitter, and R is the range from the transmitter/receivers to the target. If S is defined as the minimum power detectable at the receiver, then the R is the maximum detectable range. Equation (11) can be rewritten as follows:

$$R = \sqrt[4]{\frac{\gamma}{S}} \sqrt[4]{P_t} \quad (12)$$

Next, we assume that the transmitting power becomes δP_t, that is δ times. Then, maximum detectable range R' can be rewritten in terms of R as follows:

$$R' = \sqrt[4]{\frac{\gamma}{S}} \sqrt[4]{\delta P_t} = \sqrt[4]{\delta} R \quad (13)$$

As mentioned above, $|S_{\text{sum}}(\theta, t)|$ in Equation (9) is the gain of the array, which is related to δ. When the gain of the electric power is $|S_{sum}(\theta, t)|$, the maximum detectable range R' can be calculated from Equations (9) and (13).

As a result, from Equations (10) and (8), we obtain the following equation:

$$\left[\prod_{k=1}^{K} \sum_{n=1}^{N} P(\tilde{r}_{kn} | \hat{r}_k) \right] \cdot D_p(x, y) \quad (14)$$

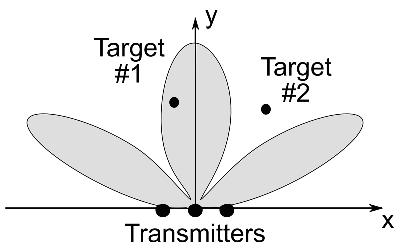

Figure 7. Directivity response pattern and targets

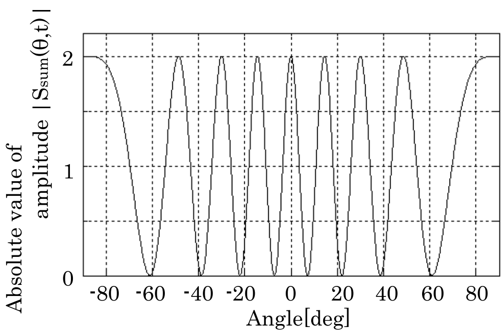

Figure 8. Designed directivity response pattern

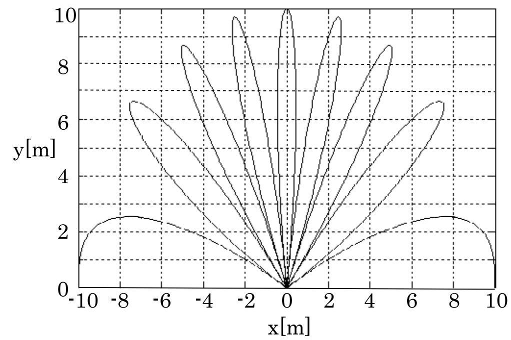

Figure 9. Detectable area

Table III
PARAMETERS OF THE TRANSMITTER

Frequency: f_0	24 [GHz]
Number of transmitters: L	3
Width of array [m]	0.1
Element positions [m]: B_l	-0.05, 0, 0.05
Amplitude control: A_l	0.5, 1, 0.5

Equation (14) gives the existence probability considering the directivity of the transmission signal. The generation of the directivity often results in null directions. In order to compensate for the null directions, the direction of the main lobe of the directivity response pattern is changed a small number of times in order to change the directivity in a trial, such as beam scanning.

V. NUMERICAL EVALUATION

We evaluate the characteristics of the EPEM algorithm and the EPEMD algorithm from the viewpoint of error reduction.

We designed the directivity pattern as shown in Figure 8. We then converted the directivity pattern into the detectable area using Equations (9) and (13). The detectable area is shown in Figure 9. In the simulations, we assume that the maximum value of the $|S_{sum}(\theta, t)|$ is 2 and that the maximum detectable range R' is 10 m. As mentioned in Section IV, it is necessary to change the directivity in a detection trial such as beam scanning in order to detect targets over a wide area. However, for the evaluation of the position estimation characteristics of the algorithms, only one fixed directivity pattern is simulated. The parameters of the transmitter are shown in Table III. Considering that targets exist in the near field, the width of the transmission array is set to 0.1 m. We simulate two cases. In Case 1, the target is located at (0,9) [m], which is a relatively long distance from the sensors. In Case 2, the target is located at (0,2) [m], which is short. For the evaluation of the estimation errors, we use the variance of the distribution of the estimated positions, which are used in Section III-B, as the performance measure. The other simulation parameters are as listed in Table I.

The results for the variance are shown in Table IV. These variances are derived from the distribution of the estimated positions. For example, the obtained distributions in Case 1 are shown in Figure 10,11. From Table IV, in the case of the EPEMD algorithm, the variance of both the x- and y-directions can be reduced compared to the EPEM algorithm. Moreover, in the case of a long distance, the reduction in variance is large compared to the case of a short distance. In particular, the variance in the x-direction, which is the direction of the arrangement of the receivers, can be decreased significantly.

VI. CONCLUSION

We considered the position estimation algorithm for targets that exist in the near wide area. A problem exists in that the position estimation error in the direction of the arrangement of receivers is large if the receivers are arranged along a straight line. In order to reduce this error, the proposed EPEMD algorithm uses the target existence probability, which is calculated based on range, and the directivity information of the transmitter. Computer simulations revealed that the proposed algorithm achieved low errors. Moreover, the error in the direction of the receivers arrangement was effectively reduced as intended.

As presented in Table IV, the variance in the y-direction is very small, which indicates that the multiple networked sensors have significant potential for application. Compared to the error in the y-direction, the error in the x-direction is relatively large. As the future work, we will continue to reduce this error. We will first find a suitable directivity pattern for the EPEMD algorithm. Next we will apply the

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Table IV
MEAN AND VARIANCE VALUES

	Target position [m]	Method	Var[$\hat{x}$]	Var[$\hat{y}$]
Case 1	(0,9)	Conventional	0.240	0.00237
		EPEMD	0.0339	0.00179
Case 2	(0,2)	Conventional	0.0139	0.00216
		EPEMD	0.0115	0.00227

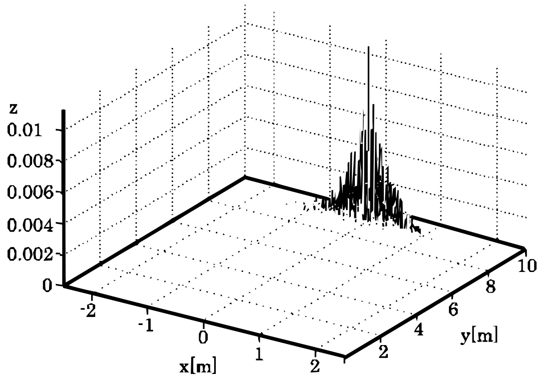

Figure 10. Distribution of estimated positions (Conventional, Case 1)

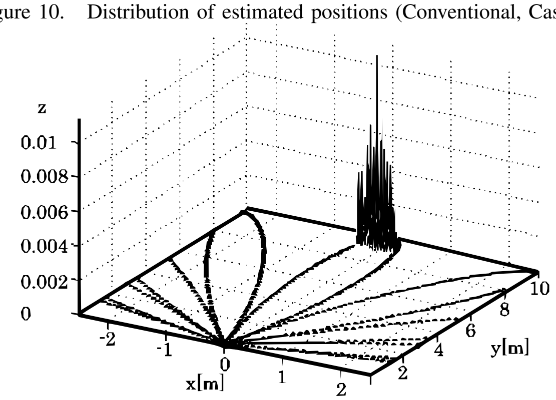

Figure 11. Distribution of estimated positions (EPEMD, Case 1)

reflected signals, which are often dealt with as multipath signals, to the EPEMD algorithm. The reason is that the multipath can surround the target whereas the receivers cannot surround the target.

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