

## Research Article

# An AOA and Orientation Angle-Based Localization Algorithm for Passive RFID Tag Array

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This paper proposes an indoor localization algorithm based on AOA (Arrive of Angle) and orientation angle (OA) for passive UHF RFID (Ultra-High Frequency Radio Frequency Identification) tag array. By utilizing a uniform linear tag array (ULA), the AOA, which is defined as the angle of the reader relative to the tag array, can be estimated by the Multiple Signal Classification (MUSIC) algorithm. The relationship between AOA, OA of the tag array, and the direction angle (DA) between each reader antenna to the geometric center of the tag array is analyzed, and an OA retrieval method based on rotating the coordinate system is proposed to calculate DA. The tag array localization is finally acquired by the DA of each antenna. Simulation and experiment results show that the proposed algorithm can achieve decimeter-level localization accuracy. The proposed algorithm achieves a mean accuracy of 0.216 m, which is a significant improvement compared with the traditional AOA localization algorithm.

## 1. Introduction

With the advantages of low cost and high data rate, radio frequency identification (RFID) technology plays an important role in the perception layer of the internet of things (IoT) [1], which has been widely used in many fields, such as supply chain management (SCM) [2], logistics management, and warehouse management [3]. Combining target recognition and accurate position information is generally beneficial to these applications. The researches on RFID-based localization technology [4, 5] have important practical significance.

In recent years, scholars have conducted a lot of research on how to use RFID tags to achieve localization. In the RFID-based localization system, one or more tags are attached to an object. The received signal strength (RSS) and the phase information of tags are exploited by various localization systems. In [6, 7], they deploy reference tags with fixed position in advance. The target's position is estimated by  $k$  reference tags whose RSS are the most similar

to that of target tag. However, the RSS is not a reliable indicator, it is susceptible to the tag's orientation, antenna gain, and multipath environment. Thus, the RSS-based system is difficult to achieve fine-grained localization. Although some RSS-based methods can achieve high localization accuracy, these methods need to deploy a considerable number of reference RFID tags [8, 9]. Compared with RSS, the phase of the signal has higher resolution and noise tolerance, which is a better choice to realize high accuracy localization. In [10], the phase differences between two antennas are collected to build hyperbolas. The position of the tag can be estimated by the intersections of these hyperbolas. Another localization method based on the direction of tag is proposed in [11]; the phase difference collected by antenna array is used to estimate the direction of the tag. In the phase-based methods, to solve the ambiguity introduced by the phase, the spacing between two antennas should be within half wavelength, and it is quarter wavelength for the commercial off-the-shelf (COST) UHF RFID with monostatic antennas as it is a round-trip in this system. However, the

size of commonly-used circular polarization antenna is hard to meet this stringent requirement. Such a COST reader cannot satisfy this spacing constraint. To solve this problem, RFID tag array is undoubtedly a better choice.

Compared with a reader antenna, the size of RFID tags is smaller; the distance between two tags can be easily restrict within quarter wavelength or narrower. Moreover, benefiting from the low cost of the RFID tag, the tag array has a lower cost contrasted with the antenna array [12, 13]. In recent years, tag arrays have been widely used in 3D reconstruction [14], gesture recognition [15], and human motion sensing [16, 17]. Besides, tag array is also a great choice for indoor localization systems. Yang et al. localized the target by the AOA of two antennas which are estimated from the phase information of the tag array [18]. However, when the orientation angle (OA) of the tag array is unknown, the localization accuracy will deteriorate dramatically. Therefore, how to estimate the OA tag array is a key issue. To solve this problem, this paper proposes a novel AOA-based indoor localization system, which can achieve an accuracy of decimeter-level. The main contributions of this paper are as follows:

- (i) Different from the traditional tag array localization model, the OA of the tag array is taken into consideration in our localization model, and targets can be localized with an unknown OA
- (ii) An orientation angle (OA) retrieval algorithm for the tag array is proposed, which uses AOA estimation results of multiple reader antennas to accomplish the OA retrieval for tag arrays

## 2. Phase Difference in RFID Tag Array

Most COST RFID readers can collect the phase information of the tag when inventorying the tag, as shown in Figure 1. The measured phase value is the offset of the signal sent and received by the reader antenna which includes the phase introduced by the round-trip propagation between the reader and tag and the phase error introduced by the reader transmitter circuit, the receiver circuit, and the tag. Besides, the measured phase is a value between 0 and  $2\pi$  due to phase wrapping. The measured value cannot directly represent the distance information between the antenna and the tag. The received phase can be modelled as [19]

$$\varphi_i = \text{mod} \left( \frac{4\pi r}{\lambda} + \varphi_{Tx} + \varphi_{Rx} + \varphi_{\text{tag}}, 2\pi \right), \quad (1)$$

where  $\lambda$  is the wavelength,  $r$  is the distance between tag and reader antenna,  $\varphi_{\text{tag}}$  is the phase error introduced by tag's reflection characteristics, and  $\varphi_{Tx}$  and  $\varphi_{Rx}$  are the phase errors introduced by transmitter and receiver, respectively.

In general, most of COTS RFID readers work with monostatic antennas that simultaneously transmit RF signals to power up RFID tags and then receive their backscatter signals. For the measured phases of two tags collected by one antenna, the errors introduced by transmitter and

receiver are the same. Meanwhile, to eliminate the phase ambiguity between two tags, we restrict the distance  $d$  between two adjacent tags within  $\lambda/4$ , which means that the difference of two tags' round-trip distance is less than  $\lambda$  [20]. According to equation (1), the phase difference can be represented as

$$\Delta\varphi_{i,i+1} = \varphi_i - \varphi_{i+1} = \frac{4\pi(r_i - r_{i+1})}{\lambda} + \varphi_{\text{tag}_i} - \varphi_{\text{tag}_{i+1}}. \quad (2)$$

The errors introduced by the tag arise from the tag's circuit, mutual coupling, and the signal incident direction [20], which can be regarded as

$$\varphi_{\text{tag}} = \varphi_{\text{sel}} + \varphi_{\text{in}} + \varphi_{\text{cop}}, \quad (3)$$

where  $\varphi_{\text{sel}}$ ,  $\varphi_{\text{in}}$ , and  $\varphi_{\text{cop}}$  are the errors introduced by tag's circuit, signal incident direction, and mutual coupling between tags. Tags of the same type have similar circuit construction, so  $\varphi_{\text{sel}_i} \approx \varphi_{\text{sel}_j}$ . For the same reader antenna, the signal incidence direction for two very close tags (for the UHF RFID  $d \leq \lambda/4 \approx 8.11$  cm) can be regarded as equal. From Tagyro [21], strong mutual coupling in the tag array will affect the measured phase significantly and make it hard to detect the tags. When the spacing of the tags increases, the mutual coupling on measured phase difference is limited. For the same pair of tags, their mutual coupling is identical [22]; the measured phase difference between two tags is independent to the coupling voltage and impedance [18]. Although mutual coupling has a great effect on the measured phase, the effect of mutual coupling on the phase difference can be attenuated significantly, which has less impact on localization.

## 3. System Design

*3.1. Localization Model.* The OA of the tag array is not considered in the traditional tag array-based localization models [18], in which it is assumed that the AOA estimation result  $\theta'_i$  of the tag array is equal to the direction angle  $\beta_i$  of the tag array relative to the antenna  $i$ . According to the geometric relationship, the positioning of the tag array can be estimated by the AOA estimation of the two reader antennas of the tag array. However, in a real localization scenario, the OA of the tag array cannot be known in advance, and using this localization model will generate a large localization error. To solve this problem, a localization method based on pose retrieval of tag arrays is proposed in this paper.

In our system, we deployed  $M$  antennas and a RFID tag array in the environment.  $N$  tags are uniformly attached to the target to form a uniform linear RFID tag array (ULA), and all tags can be inventoried from both sides. As shown in Figure 2, the tag array is used to acquire the AOA ( $\theta'_i$ ) between the center of the array and antenna- $i$ , the OA of the tag array is  $\alpha$ , and the DA of the tag array for antenna- $i$  is  $\beta_i$ . Theoretically, based on  $M$  ( $M \geq 3$ ) AOA values and

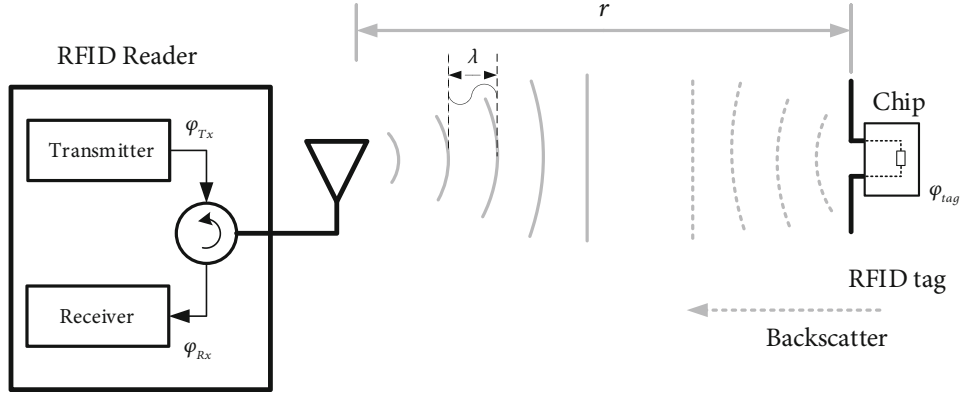


FIGURE 1: Illustration of the RFID backscatter link.

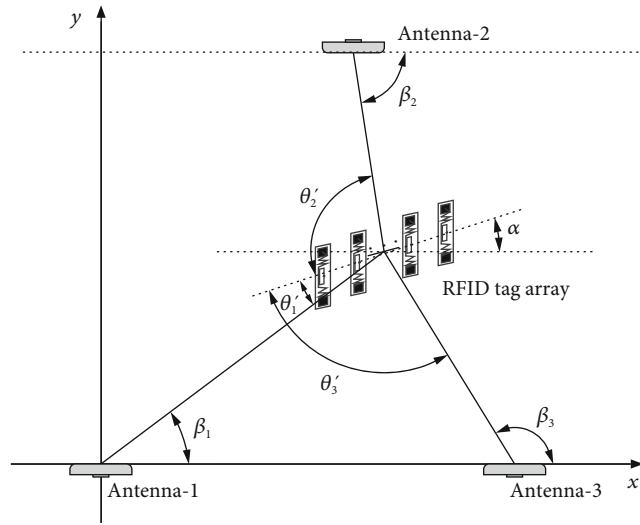


FIGURE 2: Localization model.

the fixed reader antenna positions, the OA of tag array can be accurately determined. The DAs of antennas are

$$\begin{cases} \beta_1 = \theta'_1 + \alpha, \\ \beta_2 = \theta'_2 - \alpha, \\ \beta_3 = \theta'_3 + \alpha. \end{cases} \quad (4)$$

If the positions of antennas are fixed, the idea is to use the DAs of each antenna to determine the position of tags. Supposing that the position of the antenna is  $(x_i, y_i)$  and the tag array's position is  $(x_c, y_c)$ , the DAs of antennas satisfy

$$\begin{cases} \cot(\beta_1) = \frac{y_c - y_1}{x_c - x_1}, \\ \cot(\beta_2) = \frac{y_c - y_2}{x_c - x_2}, \\ \cot(\beta_3) = \frac{y_c - y_3}{x_c - x_3}. \end{cases} \quad (5)$$

Since the phase measurements would be inevitably influenced by various noise sources, three lines defined by  $\beta_1, \beta_2$ , and  $\beta_3$  will not intersect at one point. Three different solutions  $\{(x_{c1}, y_{c1}), (x_{c2}, y_{c2}), (x_{c3}, y_{c3})\}$  can be obtained from Equation (5), and the average value is taken as the localization result of the tag array.

The main challenge of the system is how to effectively estimate the AOA values of antennas and the OA of tag array. In this paper, a new tag array-based localization system is designed, which can estimate the OA of the array. The details of tag array AOA estimation and OA estimation will be discussed in the following sections.

**3.2. Tag Array AOA Estimation.** The scenario of AOA estimation for single antenna is shown in Figure 3. The spacing  $d$  between adjacent tags in the array is restricted to be within  $\lambda/4$ , which is much less than the distance  $r$  between reader antenna and tag array ( $d \ll r$ ) and satisfies the far-field condition. The signal arrived at the tag array can be regarded as plane wave. Assuming that there are  $K$  paths in the indoor

environment, the received signal backscattered from tag array at time  $t$  can be modelled as

$$X(t) = \sum_{i=1}^K a(\theta_i) s_i(t) + n_i(t) = As(t) + n(t) \quad (6)$$

where  $\theta_i$  is  $xx$ ,  $A = [\alpha(\theta_1), \alpha(\theta_2), \dots, \alpha(\theta_K)]$  is the manifold matrix,  $s(t) = [s_1(t), s_2(t), \dots, s_K(t)]^T$  is the source signal vector, and  $n(t)$  is the noise. Taking the first element of the array as the reference, the received signal can be reconstructed by the phase difference:

$$\hat{X}(t) = \left[ 1, e^{-j\varphi_{12}(t)}, \dots, e^{-j\varphi_{1k}(t)}, \dots, e^{-j\varphi_{1N}(t)} \right]^T, \quad (7)$$

where  $\varphi_{1k}(t)$  is the phase difference of the  $k$ -th tag to the first reference tag. As the tags in the array are close to each other, the multipath effect of each tag is similar. Thus, the phase difference can reduce both the multipath effect and the coupling effect. The RFID communication is a round-trip link, so the steering vector for the uniform tag array can be expressed as

$$\alpha(\theta) = \left[ 1, e^{-j4\pi(d/\lambda) \sin \theta}, \dots, e^{-j4\pi((N-1)d/\lambda) \sin \theta} \right]^T. \quad (8)$$

Due to the coherent multipath signal, the steering vector and the noise subspace are not completely orthogonal, which affects the estimation of the signal source direction. To further reduce the effect of coherent multipath, spatial smoothing method is adopted. The uniform linear tags array is divided into  $p$  subarrays, and the number of elements in each subarray is  $M$  ( $M \geq K + 1$ ). The covariance matrix of  $l$ -th subarray is given by

$$R_l = A_M(\theta) D^{(l-1)} R_s \left( D^{(l-1)} \right)^H A_M^H + \sigma^2 I, \quad (9)$$

where  $D = \text{diag} [e^{-j4\pi d \sin \theta_1/\lambda}, e^{-j4\pi d \sin \theta_2/\lambda}, \dots, e^{-j4\pi d \sin \theta_K/\lambda}]$  is called displacement operator.  $A_M$  is a  $M \times K$  manifold matrix of the sub-array,  $R_s$  is the covariance matrix of signal, and  $I$  is the unit matrix and  $\sigma^2$  is the power of noise. The covariance matrix after spatial smoothing is

$$R_s^f = \frac{1}{p} \sum_{i=1}^p D^{(i-1)} R_s \left( D^{(i-1)} \right)^H. \quad (10)$$

Performing eigendecomposition on  $R_s^f$ , equation (8) can be rewritten as

$$R_s^f = U_s \Sigma_s U_s^H + U_N \Sigma_N U_N^H, \quad (11)$$

where  $U_s$  is the signal subspace formed by the eigenvector associated with the large eigenvalue and  $U_N$  is the noise subspace corresponding to the small eigenvalues. By searching all arrival vectors that are orthogonal to the noise subspace,

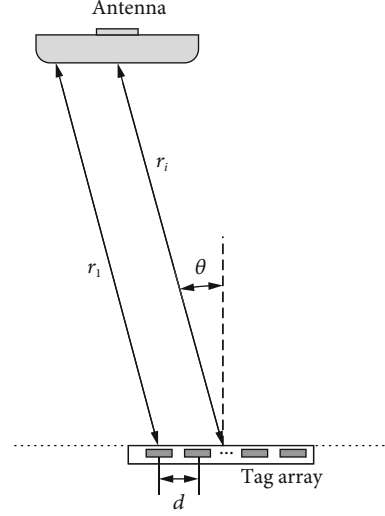


FIGURE 3: Antenna's AOA estimation.

the direction of antenna can be estimated by

$$\theta_{Tx} = \max_{\theta} \frac{1}{A_M(\theta)^H U_N U_N^H A_M(\theta)}. \quad (12)$$

According to the geometric relationship, the AOA of antenna is  $\theta' = \pi/2 - \theta_{Tx}$ .

**3.3. OA Estimation.** In this part, we will provide the details of our proposed OA retrieval algorithm based on a tag array. In an  $x-y$  coordinate system, OA is the angle of intersection between a line parallel to the positive  $x$ -axis and the line going through tag array. Instead of viewing the antennas  $A_1, A_2, A_3$  in  $x-y$  coordinate system, we construct virtual antennas  $VA_1, VA_2,$  and  $VA_3$  in  $x'-y'$  coordinate system. As shown in Figure 4, the  $x'-y'$  coordinate is obtained by rotating  $x-y$  coordinate counterclockwise through the origin by  $\alpha(m) = (m-1) \times \Delta\alpha - \pi/2$ , where  $\Delta\alpha$  is the rotation interval and  $m$  is an integer. Assuming that the OA of tag array is limited, the range of  $\alpha(m)$  is  $[-\pi/2, \pi/2]$ ,  $m$  is in  $[1, M]$ .  $\alpha(m)$  represents the searching start point when  $m=1$ ;  $M$  is inversely proportional to the rotation interval  $\Delta\alpha$  and equals to  $[\pi/\Delta\alpha]$ , where  $[\cdot]$  is the rounding operation.

As shown in Figure 4, assuming that the position of antennas in  $x-y$  coordinate is  $A_i = (x_i, y_i)$ , after rotating an angle  $\alpha(m)$ , the new position in  $x'-y'$  coordinate is  $A_i(m) = (x_i(m), y_i(m))$ , and the transformation from  $A_i$  to  $A_i(m)$  can be written as

$$\begin{bmatrix} x_i(m) \\ y_i(m) \end{bmatrix} = R[\alpha(m)] \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \quad (13)$$

where  $R[\alpha(m)]$  is the counterclockwise rotation matrix, which can be described as

$$R[\alpha(m)] = \begin{bmatrix} \cos \alpha(m) & \sin \alpha(m) \\ -\sin \alpha(m) & \cos \alpha(m) \end{bmatrix}. \quad (14)$$

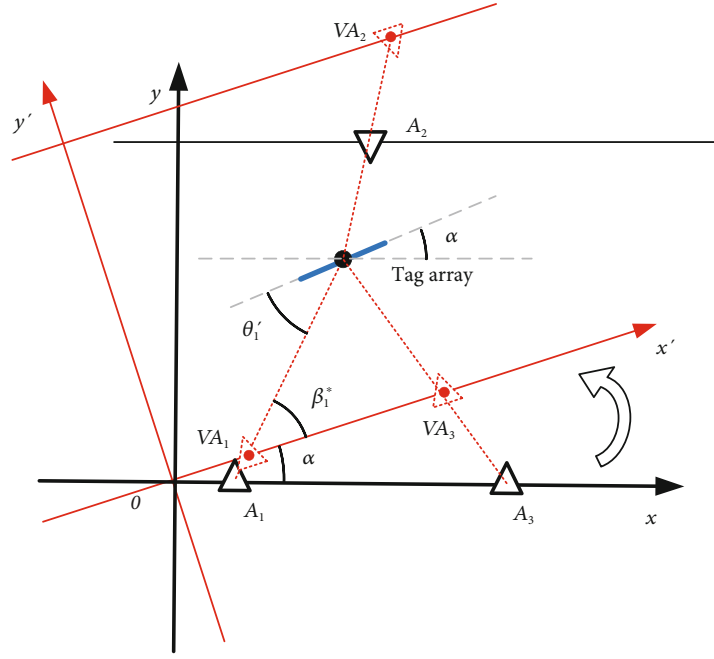


FIGURE 4: Rotation of coordinate.

The position of virtual antenna  $VA_i(m)$  is defined as the intersection of  $x'$ -axis and the line  $l_i(m)$ .  $l_i(m)$  is built by antenna  $A_i(m)$ , and it is AOA value  $\theta'_i$ , which is obtained by equation (12). In the  $x' - y'$  coordinate, it can be expressed as

$$\begin{cases} l_1(m): y' = \tan \theta'_1 \times [x' - x_1(m)] + y_1(m), \\ l_2(m): y' = \tan (\pi - \theta'_2) \times [x' - x_2(m)] + y_2(m), \\ l_3(m): y' = \tan \theta'_3 \times [x' - x_3(m)] + y_3(m). \end{cases} \quad (15)$$

As shown in Figure 5, we deployed three antennas in the localization system. The three lines  $\{l_1(m), l_2(m), l_3(m)\}$  built from Equation (15) will have three intersections  $\{C_1(m), C_2(m), C_3(m)\}$ . The sum of Euclidean distance between the three intersections is defined as  $dist(m)$ :

$$dist(m) = \|C_1(m) - C_2(m)\| + \|C_1(m) - C_3(m)\| + \|C_2(m) - C_3(m)\|. \quad (16)$$

Theoretically,  $x'$ -axis is parallel to the tag array when the rotation angle of the  $x' - y'$  coordinate equal to the OA of tag array. In this case, as shown in Figure 4, we have  $\beta_i(m) = \theta'_i$ ; the DA is equal to AOA for the same antenna; the three lines will have a unique intersection  $dist(m) = 0$ . However, when taking the noise effects into consideration, the three lines will no longer intersect to one point. Thus, a method

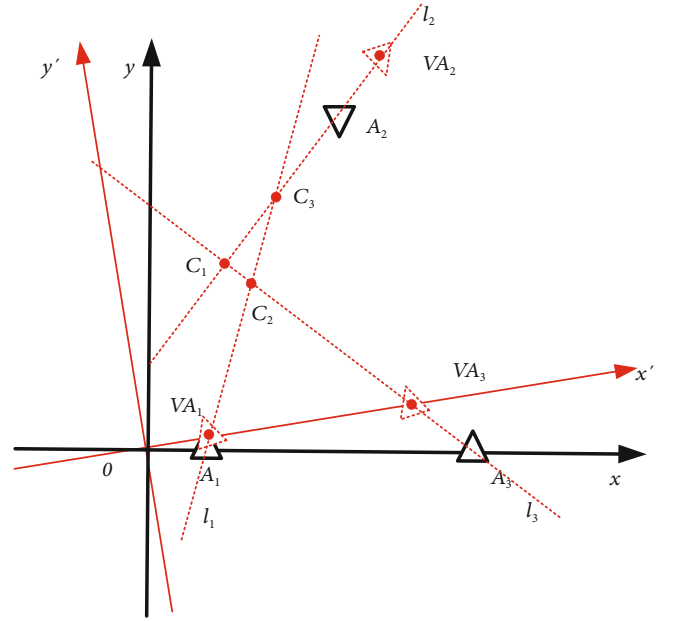


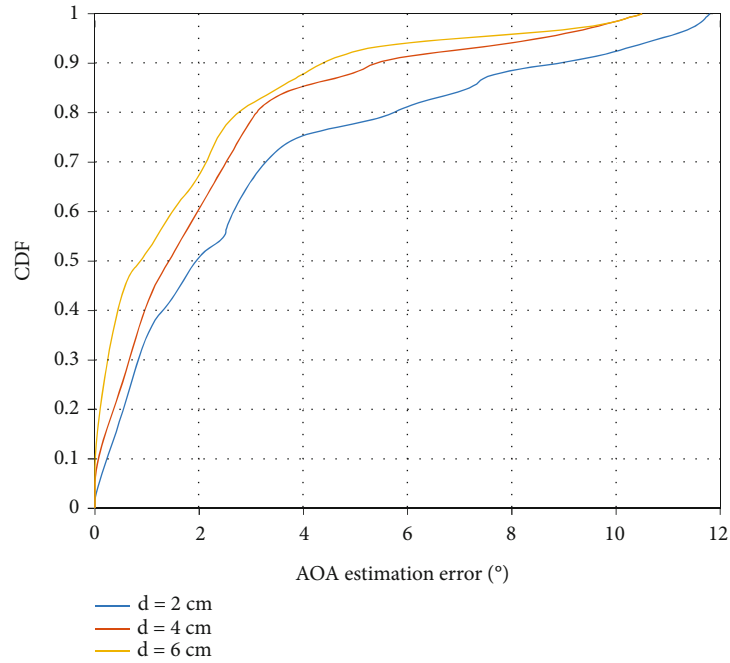
FIGURE 5: Orientation angle estimation.

based on the rotation of coordinate is employed to estimate the index of OA

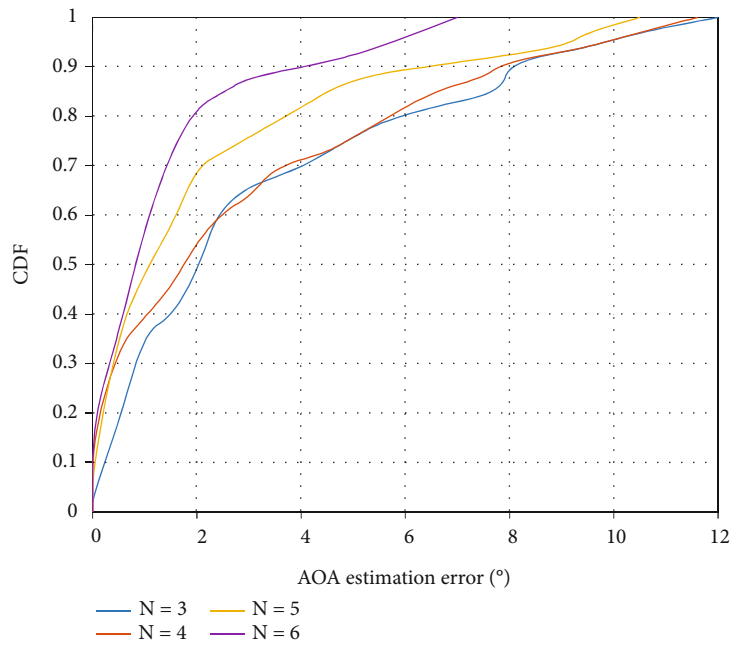
$$m^* = \underset{m \in [-90, 90]}{\operatorname{argmin}} (dist(m)). \quad (17)$$

## 4. Experiments Results

Experiments were carried out in a typical indoor scenario with Impinj R420 UHF RFID reader and C90G tags (with Monza 4QT chip). The reader can extract information from



(a)



(b)

FIGURE 6: Evaluation of AOA estimation: (a) AOA estimation error of different tag spacing; (b) AOA estimation error of different number of tag array.

tags, including phase angle, RSSI, and Doppler shift based on a Low-Level Reader Protocol (LLRP). A Lenovo laptop with i7-5500u CPU is used for signal processing; the software used in the experiment is developed based on official library, which allows the computer to communicate with the RFID reader. Similar to [23], the experiment considered  $2\pi - \varphi_i'$  as  $\varphi_i$ , where  $\varphi_i'$  is the phase value measured by Impinj

R420. Besides, to determine some of the fixed variables, several detailed benchmarks are established.

**4.1. AOA Estimation.** The AOA estimation result of the RFID tag array is the basis for localization. In order to evaluate impacts of the tag spacing and tag number of the RFID tag array on the AOA estimation performance, experiments



FIGURE 7: Experiment setup.

were carried out by placing a reader antenna at a fixed distance of 1.5 m in front of the tag array, and the tag array was rotated in the range of  $[-70^\circ, 70^\circ]$  with  $5^\circ$  interval.

**4.1.1. Impact of Tag Spacing.** The mutual coupling between the tags in the RFID tag array is an important factor affecting the phase of the backscattered signal, and this effect will gradually decrease with the increase of the tag spacing. To explore the effect of tag spacing on the AOA estimation, four RFID tags were constructed with different spacings to construct a tag array. Experiment results are shown in Figure 6(a); the array with larger spacing has higher AOA estimation accuracy than the case with smaller spacing. The average AOA estimation error corresponding to the spacing of 2 cm, 4 cm, and 6 cm is  $3.3^\circ$ ,  $2.8^\circ$ , and  $2.19^\circ$ , respectively.

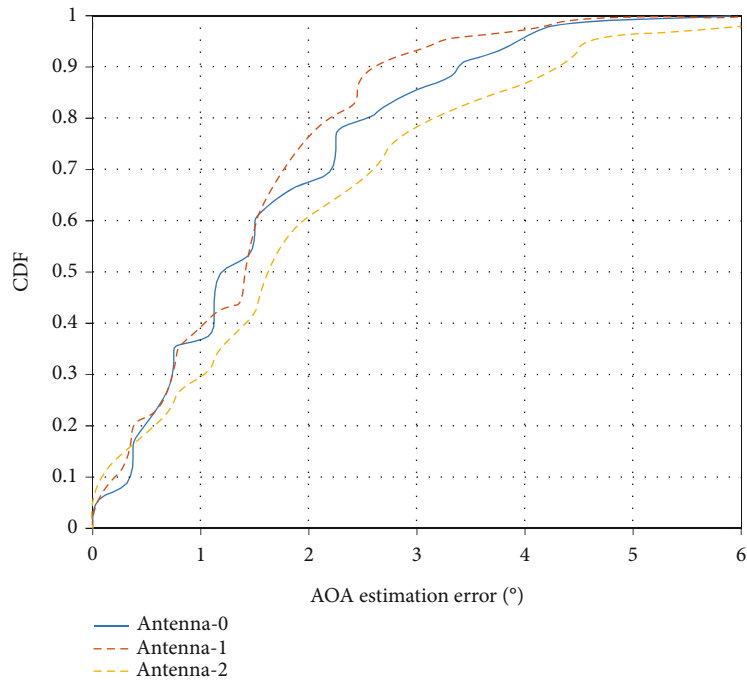
**4.1.2. Impact of Tag Number.** The number of array elements in the MUSIC algorithm is also a key factor affecting the accuracy of AOA estimation. In the experiment, the tag spacing was set to 4 cm. The results of AOA estimation with different tag number are shown in Figure 6(b). It can be seen that with the increase of the tag number, the error of the AOA estimation of the tag array gradually decreases. The average errors of the AOA estimation for the tag number of 3, 4, 5, and 6 are  $3.45^\circ$ ,  $3.15^\circ$ ,  $2.42^\circ$ , and  $1.77^\circ$ , respectively.

**4.2. Localization.** To evaluate localization algorithm based on RFID tag array, we built a real localization system in a  $4\text{ m} \times 4\text{ m}$  indoor area. The reader part consists of three circular polarized antennas and a Impinj R420 RFID reader. As shown in Figure 7, considering the width of the target object, six tag are adopted for the RFID tag array, where the spacing  $d$  is 4 cm. The experiment environment is shown in Figure 7;

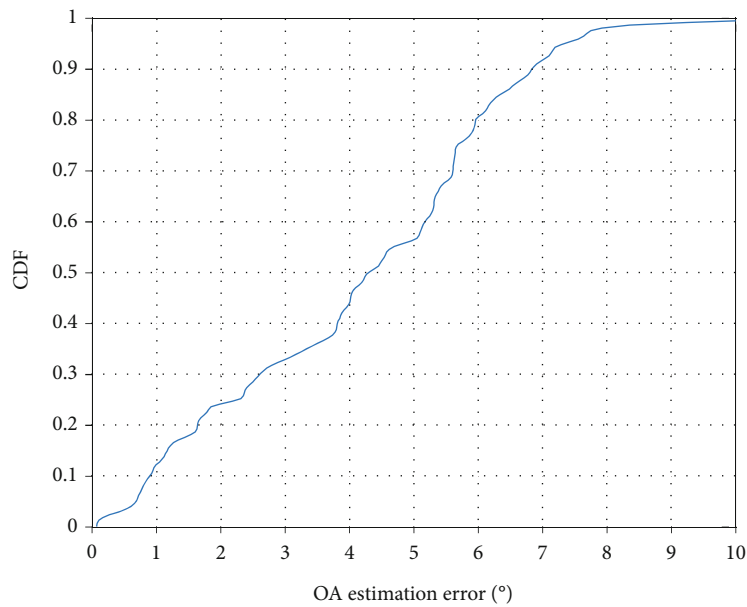
the positions of antennas are  $A_0(0.5\text{ m}, 0\text{ m})$ ,  $A_1(2\text{ m}, 4\text{ m})$ , and  $A_2(3.5\text{ m}, 0\text{ m})$ , which are distributed on the boundary of the measurement area.

Under the condition that each tag in the tag array can be read correctly, we carried out a series of experiments in different positions with different OAs, the statistical result is shown in Figure 8. The CDFs of the AOA and OA estimation error are shown in Figure 8; for the three antennas, the mean AOA estimation error is about  $2.7^\circ$ . Antenna-1 is at the center of the boundary, so the AOA estimation is slightly better than other two antennas. For the OA estimation result shown in Figure 8(b), 80% OA estimation error is less than  $6^\circ$ , and the mean OA error is  $4.35^\circ$ . The CDF of localization error is shown in Figure 9(a), the mean  $x$ -axis error and  $y$ -axis error are 0.15 m and 0.13 m, respectively. Furthermore, the average localization error is 0.216 m. As shown in Figure 9(b), compared with the traditional AOA localization algorithm in [18], the OA estimation-based localization algorithm has higher positioning accuracy. The mean localization errors for the proposed algorithm and Ref. [18] are 0.216 m and 0.342 m, respectively. The proposed method can achieve higher localization accuracy by taking the OA of the tag array into consideration when compared to Ref. [18].

**4.3. Cost of Localization.** In the RFID localization system proposed in this paper, an ULA is constructed by RFID tags. Benefiting from the low cost of UHF RFID tags, the cost of the proposed system is lower than those of other localization systems. As shown in Table 1, we compared the hardware cost and average localization accuracy of several different localization systems. Compared with commercial equipment, the cost of customized equipment is generally higher.



(a)



(b)

FIGURE 8: Results of angle estimation: (a) CDF of AOA estimation error; (b) CDF of OA estimation error.



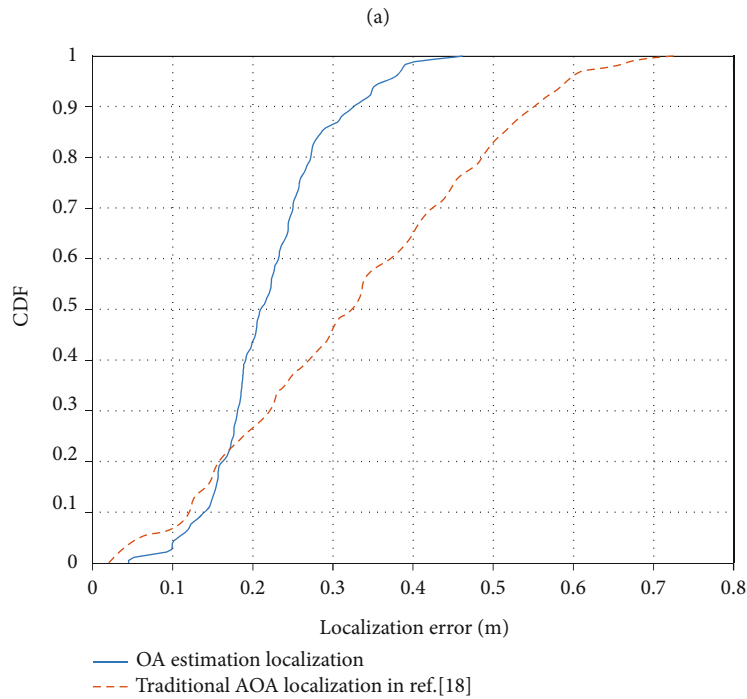
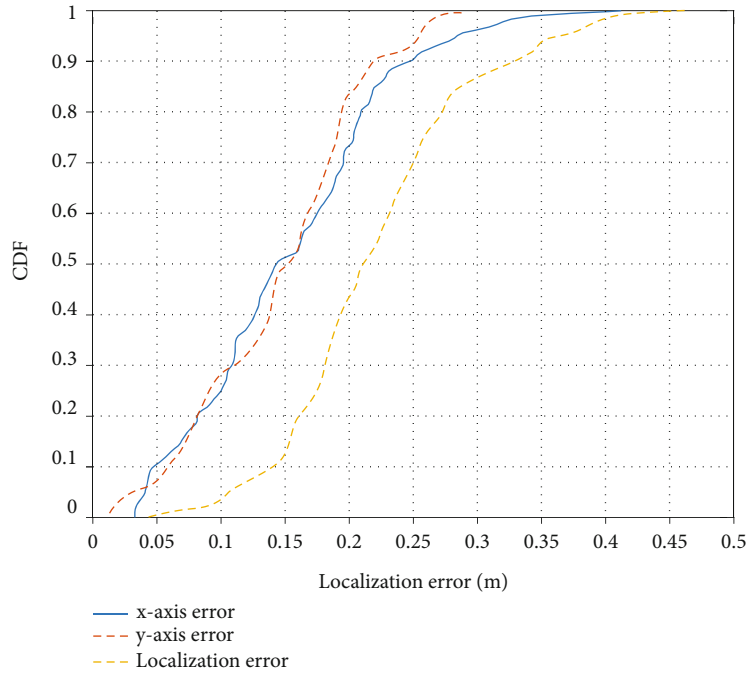


FIGURE 9: Localization results: (a) CDF of localization error; (b) comparison with the traditional localization algorithm.

TABLE 1: Comparison of localization systems.

Localization system	Hardware cost	Mean accuracy
LANDMARC [7]	4 off-the-shelf reader antennas, 1 commercial RFID reader	1~2 m
Azzouzi et al. [24]	3 custom antenna arrays, 1 commercial RFID reader	0.21 m
Povalac [25]	1 custom RFID front-end prototype, 1 commercial RFID reader	0.14 m
Peng et al. [26]	8 cost RFID readers, 2 commercial RFID readers	0.38 m
This paper	3 COST RFID antennas, 1 commercial reader	0.21 m

Among them, [24, 25] use customized special equipment, which undoubtedly increases the cost required for positioning. Systems in [7, 26] and this paper only require simple commercial equipment, and the localization cost is lower. The localization accuracy of the system proposed in this paper is higher than those in [7, 26]. Moreover, the system in this paper does not need to perform complex reference tag library construction in advance, which also greatly reduces the human cost.

## 5. Conclusions

This paper proposes a localization method based on AOA and orientation angle for passive tag array. By analyzing the relationship among AOA, OA of the tag array, and DA between each reader antenna and the geometric center of the tag array, an OA retrieval method based on rotating coordinate system is proposed to estimate DA. And the tag array position can be determined by antennas and their DAs. Simulation and experiment results show that the mean accuracy of the proposed algorithm is 0.216 m.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors do not have any possible conflicts of interest.

## Acknowledgments

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