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Localization of pallets in warehouses using passive RFID system

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Abstract: Warehouse operation has become a critical activity in supply chain. Position information of pallets is important in warehouse management which can enhance the efficiency of pallets picking and sortation. Radio frequency identification (RFID) has been widely used in warehouse for item identifying. Meanwhile, RFID technology also has great potential for pallets localization which is underutilized in warehouse management. RFID-based checking-in and inventory systems have been applied in warehouse management by many enterprises. Localization approach is studied, which is compatible with existing RFID checking-in and inventory systems. A novel RFID localization approach is proposed for pallets checking-in. Phase variation of nearby tags was utilized to estimate the position of added pallets. A novel inventory localization approach combing angle of arrival (AOA) measurement and received signal strength (RSS) is also proposed for pallets inventory. Experiments were carried out using standard UHF passive RFID system. Experimental results show an acceptable localization accuracy which can satisfy the requirement of warehouse management.

Key words: warehouse management; radio frequency identification (RFID); localization; tag phase

1 Introduction

In the past decade, the change in the global economy has significantly redefined the way that enterprises operated. The changes had a significant impact on warehouse management in supply chain. The warehouse is no longer confined to keeping a large amount of stock. Instead, small quantities of goods are delivered promptly in a short response time. Planning and control of warehouse are made more complex [1−2].

Order-picking operations impact the performance of warehouse. Position information of pallets can reduce the time cost of order-picking. However, between the time that an order is released to the warehouse and the time that it takes to reach its destination, there is ample opportunity for errors to occur in both accuracy and completeness when using manual operations. Therefore, inventory is performed for calibration. Generally, automatic inventory operations only calibrate the type and quantity of the goods, not the position. Even more, in a random storage or a class-based storage warehouse, the managers lack automatic means to know where their pallets are [3].

RFID technology has potential of closing some of the information gaps in the supply chain. Passive RFID tags are widely used for their low cost and smaller size [4]. RFID-based warehouse management systems were designed to retrieve item information and handle warehouse operations in both time-saving and cost-effective manner [5−8]. However, the fact that RFID can be used for pallets localization is not efficiently utilized in warehouse.

Some classic wireless location methods have been studied to apply in RFID systems [9−10]. Generally, RFID localization techniques use received signal strength (RSS) to estimate the distance from tags to the reader [11−18]. From a theoretical point of view, RSS is an excellent approach to estimate the distance. However, the RSS value is sensitive to the environmental conditions and the tagged object properties. It is also affected by the orientation of the tag. Time of arrival (TOA) based approaches were also applied in RFID system [19−22]. But a precise time measurement is needed which is hard to achieve in passive RFID system due to the defined low signal rate of Gen 2 & 18000-6C protocol. Phase-based angle of arrival (AOA) measurement was also used in RFID localization [23−25]. However, phase information is very sensitive to the multi-path propagation. The indoor UHF RFID channels are often affected by non-line-of-sight (NLOS) paths, which lead to large phase bias and AOA measurement errors.

Checking-in and inventory are two important processes in warehouse operations. This work presents phase-based localization approach which is compatible with existing RFID checking-in and inventory system. Standard RFID reader and tags were used and the phases were measured by baseband signal of the tags. Localization using phase variation approach was

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proposed for pallets checking-in. Inventory localization approach combing AOA measurement and RSS was proposed for pallets inventory.

2 Current warehouse environment

Since 1990s, the mode of production in enterprises has changed from the traditional mass production mode led by products into the mass customization production mode to facilitate increasing global market competition. The supply chain activity has been reformulated to achieve its competitive advantage. HARMON [26] noted that warehouses should be redesigned and automated to achieve high throughput rate and high productivity, thereby reducing the order processing cost. The warehouse is no longer confined to keeping a large amount of stock. Instead, small quantities of goods are delivered promptly in a short response time.

The main warehouse activities include receiving, transfer, order-picking, calibration, sortation and shipping. Position information of pallets is important in some of these activities. For order-picking, pallet position information can efficiently reduce the travel distance and labor cost. Moreover, the decision of order routing needs the exact position of each pallet.

The receiving activity includes unloading products and moving them into warehouse. RFID-based checking-in system was widely used in warehouses for products receiving. The reader and antenna were mounted on warehouse bay door or on the floor. Information that passed over the antenna was sent to the host database. The checking-in system reduced human-based errors. Significant time-savings were experienced. Unilever, Chevrolet creative services, Kitchens, Inc, etc. have adopt the RFID checking-in system in their warehouses [5]. However, the RFID-based checking-in system can only get the code of the product. Recording of the position information still needs manual operations. The present work focuses on this problem and presents a novel RFID localization approach using phase variation.

Although information is recorded when products go in or out of the warehouse, there is ample opportunity for errors to occur. So, calibration is necessary in warehouse. The calibration activity involves calibrating the product code, quantity, etc., through inventory. How to calibrate the position of products automatically through inventory needs to be studied either. The present work focuses on this problem and presents a novel inventory localization method combing AOA measurement and RSS.

The automatic warehouse layout is shown in Fig. 1. Suppose that the warehouse consists of many aisles. The checking-in gate is installed at the side of the warehouse. The checking-in localization antennas are installed at the end of the racks. The inventory localization antennas are installed on the card. Tags corresponding to a record in the database are attached to products.

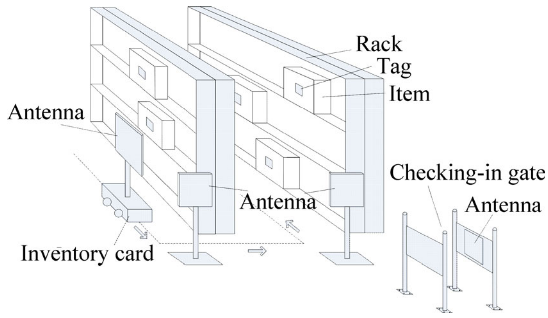

Fig. 1 Warehouse layout

3 Checking-in localization using phase variation

This section presents a localization using phase variation (LUPV) method for products checking-in localization. Reference tags were used with their signal phases recorded. The signal phase was measured by the baseband signal of the tag.

3.1 Interference on reflected tag signal

Tag-to-tag interference will cause variation in the reflected tag signal. When two tag antennas are placed close to each other, the metallic antenna of adjacent tag affects IC impedance, which will cause decrease in RSS. CHOI et al [12] used the RSS decrease of the adjacent reference tags to locate the target tag. However, the RSS decrease only occurs when the tags are closed to each other, which will need dense reference tags.

When tags are seemingly distant from one another, interaction effects can also be substantial [27]. In a simple case, tags effectively cast shadows on the tags behind them. The shadows extend laterally and grow deeper as more tags are added. This will cause a significant decrease in the signal phase of the tag in the shadows. The RSS will also decrease, but not so remarkable and regular as signal phase.

The property of the tagged item can also affect the signal of tags in the shadow. In warehouses, tags will typically be embedded in a paper or plastic label and placed on a cardboard box. Generally, sheets of dry paper will cause little influence on the signal phase of the tag in shadows. But if the target contains water or metals, the tag signal in shadows will decrease markedly.

An experiment was carried out to verify the phase decrease of tag signal, as illustrated in Fig. 2. The target tag was placed 1.5 m in front the reader antenna. First, the interference tags were attached to empty cardboard boxes and added one by one. The phase of target tag was plotted in Fig. 3. The phase of target tag decreased when the number of boxes added. The average decrease of phase was 8.4° for each box attached with tag. Then, one plastic box was placed between the target tag and the reader antenna. Each time, the box contained items of different materials and the phase was recorded. The results are plotted in Fig. 4. Items containing dry paper, water and metals were used. It can be seen that water and metals caused seriously decrease of signal phase.

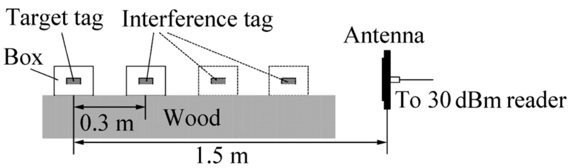

Fig. 2 Experiment to measure phase decrease of tag signal

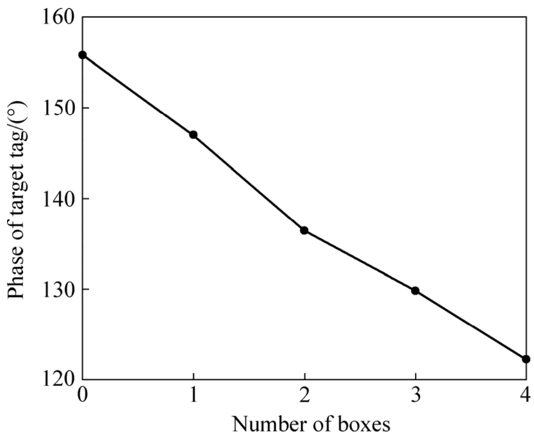

Fig. 3 Phase of target tag when empty cardboard boxes attached with reference tags were added one by one

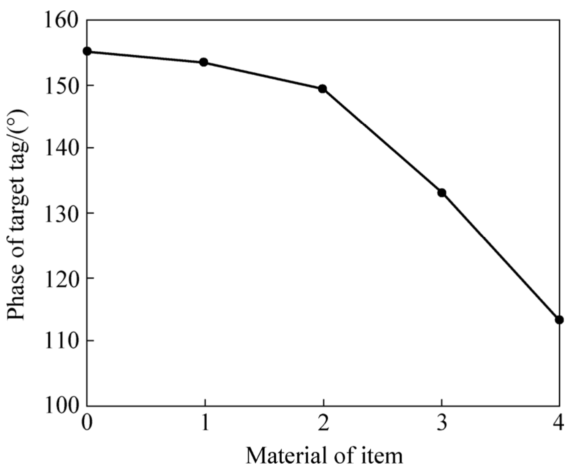

Fig. 4 Phase of target tag when a box containing items of different materials was placed between tag and antenna (index means: 0−None interference; 1−Empty plastic box; 2−Plastic box full of dry papers; 3−Plastic box full of water; 4−Plastic box containing metals)

3.2 Localization using phase variation (LUPV) approach

1) Initial stage

Supposing the shelf is in the monitoring area of a single reader antenna, as shown in Fig. 5. Let C denotes the set of IDs of reference tags in the monitoring area; P denotes the signal phase for each tag of C. At initial, the elements in C are known, and P is empty. An initial interrogation cycle gets p_{r} for all reference tags in C. The system has to handle the invisible reference tag which might become visible as the interference targets come in or out. The system maintains the information of invisible reference tags in an interrogation cycle either.

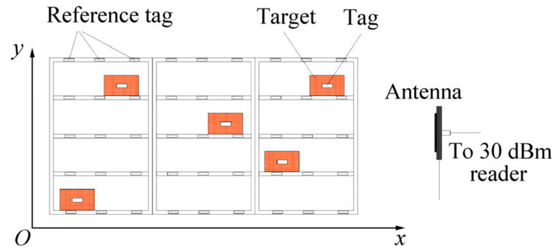

Fig. 5 Shelf setup illustration

2) Product checking-in and reference grouping stage

Supposing that each time one product is checked-in through the RFID gate and transferred to the shelf, then, an interrogation cycle is performed. The reader collects IDs and phases for all tags in the interrogation cycle, and restores the information as P^i, where i denotes the interrogation cycle. For an initial interrogation, i=0. For an unreadable reference tag, the system maintains its interrogation state as unreadable either.

In the reference grouping stage, the system selects the most useful reference tags for incoming product localization. To compare p_{r}^i with p_{r}^{i-1} and define interfered reference tags, a threshold T_{h} is needed. The threshold represents a typical phase variation from environmental factors and noise. For determination of threshold T_{h}, continues interrogations can be performed when no products is coming in or out.

$$T_{\mathrm{h}} = \max(|p_{\mathrm{r}}^j - p_{\mathrm{r}}^{j-1}|) \quad (1)$$

Then, for reference grouping the phase variation of each reference tag is obtained as

$$E_{\mathrm{r}}^i = p_{\mathrm{r}}^{i-1} - p_{\mathrm{r}}^i \quad (2)$$

For the selection of reference tags, the system compares E^i for each reference and selects interfered references as $E_{\mathrm{r}}^i > T_{\mathrm{h}}$. Invisible reference tags which were visible in the previous cycle were also selected as interfered invisible references.

However, if the target products contain metals or water, the reflection of metal or water will cause dramatic multi-path propagation of the reference tag signals. There is a high chance for a reference tag located at a long distance, to have a phase decrease exceeding the threshold T_{h} due to the reflection propagation. Actually, interfered reference tags in the shadow of the target product are spatially close. The individual reference tags should be ticked from the reference group. For ticking individual reference tags, graph theory is used. In the reference graph, each reference tag is connected to one-hop distance tags, as shown in Fig. 6.

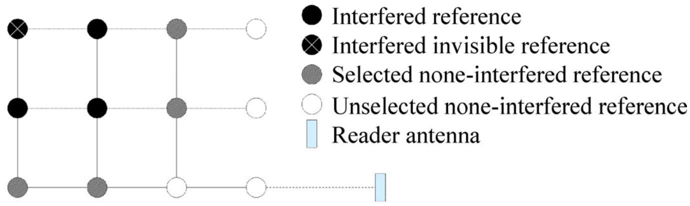

Fig. 6 Reference graph

Although all references with $E_r^i \le T_h$ can be grouped as none-interfered references, actually the system doesn't need all of them for target position calculation. For selection of the most useful none-interfered references, the reference graph can also be used. The first none interfered reference on the shortest path from the interfered reference to the reader antenna is selected for target position calculation, as shown in Fig. 6.

3) Position estimation stage

Using the interfered reference s, where $s \in S_m^i$, and selected none interfered reference t, $t \in T_n^i$, the target position can be calculated as

$$\{x^i, y^i\} = F(s_1^i) \cap F(s_2^i) \cdots \cap F(s_m^i) - F(t_1^i) \cup F(t_2^i) \cdots \cup F(t_m^i) \quad (3)$$

where $F(z)$ denotes the min Fresnel zone of z. The target position is estimated to be the center of $\{x^i, y^i\}$.

3.3 Experiments and results

1) Experimental setup

The antenna was placed 1.5 m by the side of the shelf. The dimensions of the wooden shelf were 1.8 m× 1.6 m. The shelf was placed in an ordinary office room, as illustrated in Fig. 7. In this situation, the reader antenna could cover the whole shelf area. The tags were H47 by Impinj, Inc. 45 reference tags were attached to the shelf. Each product had a tag attached to it. The RFID reader is based on a standard reader module. The main component of the reader module is INDY R2000 RFID reader chip by Impinj, Inc [28]. The frequency of the RFID reader was fixed to 915 MHz and the RF power 30 dbm. Eight targets were placed into the shelf in sequence, as shown in Fig. 8. In one interrogation circle of the reader, each tag might be read dozens or hundreds of times, and the system recorded the mean values of the tag phases.

Fig. 7 Shelf and products

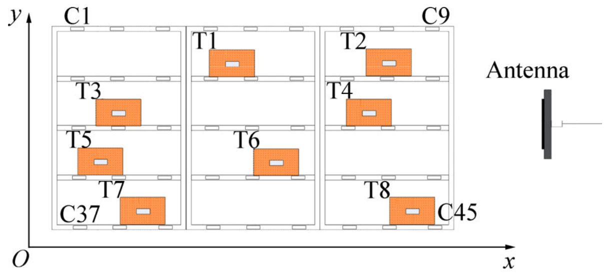

Fig. 8 Actual target position in 2-D space

2) LUPV experimental results

In the LUPV, the system measured the phase variations and selected the interfered reference tags by comparing the phase variation E_r^i with threshold T_h. T_h was set to 4.1° according to Eq. (1). Signal phase of several typical selected references are plotted in Fig. 9. For example, phase of C2 decreased from 103.5° to 97.0° when T1 appeared. So, C2 was selected as interfered reference for T1. Phase of C12 decreased from 166.2° to 160.5° when T1 appeared, and then decreased from 160.5° to 154.7° when T2 appeared. So, C12 was selected as interfered reference for both T1 and T2.

Then, none-interfered references were selected using reference graph as shown in Fig. 6. The targets positions were estimated using Eq. (3). The localization results are plotted in Fig. 10 with the grids of 0.1 m×0.1 m uniformly. The mean error of localization was 0.113 m and the maximum error was 0.174 m.

When the boxes contained water bottles, the phase decreases of interfered references would be more dramatic. For example, when T3 was an empty box, the phase of C10 decreased from 140.6° to 130.0°, and the phase of C19 decreased from 17.0° to 12.7°. C10 and C19 were selected as interfered references for T3. When T3 contained water bottles, the phase of C10 decreased from 140.6° to 120.8°, and C19 decreased from 17.0° to 5.3°. So, the interfered reference group of T3 was still C10 and C19, and the estimated position of T3 didn't

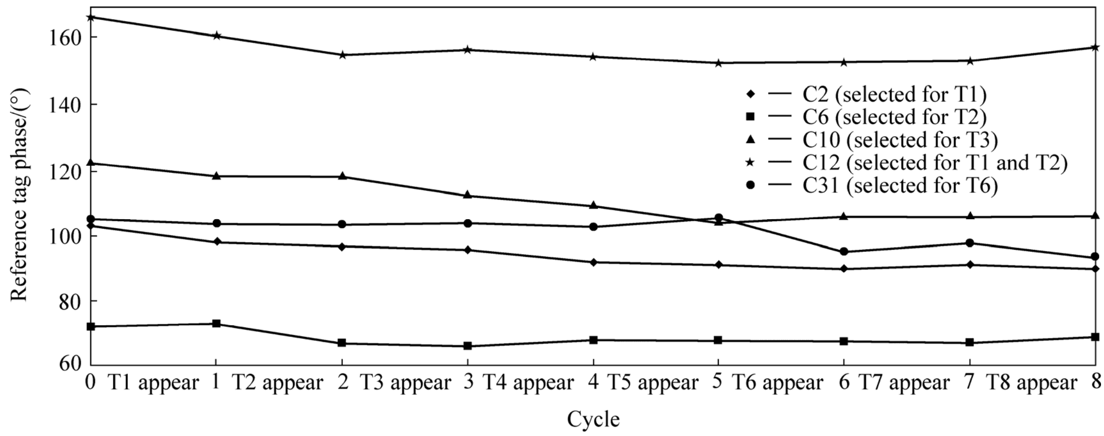

Fig. 9 Phase variation of several selected interfered reference tags (between two circles, one target was placed on the shelf)

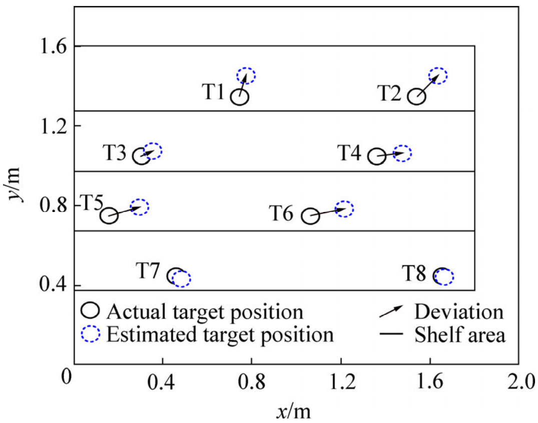

Fig. 10 Localization results of LUPV

change. Sometimes, wrong reference tags may have phase decreases exceeding the threshold due to the reflection propagation. Most of them were ticked out by using the reference graph. In our second experiment, boxes containing water bottles were used. The mean error of localization results were 0.147 m.

Table 1 shows the comparison between LUPV, KNN (k-nearest neighbor algorithm), and LDTI (Localization using detection of tag interference) [12] localization approach. Both LDTI and LUPV have improvement compared with KNN. Although the mean error of LUPV using empty boxes was not improved compared with LDTI, the maximum error of LUPV was significantly reduced. And LUPV had a better performance than LDTI when using fulfilled targets.

Table 1 Performance of LUPV

Algorithm	Material	Mean error/m	Standard deviation/m	Maximum error/m
KNN	Empty box	0.804	0.298	1.357
	Water bottle	0.684	0.230	0.962
LDTI	Empty box	0.095	0.075	0.275
	Water bottle	0.258	0.259	0.908
LUPV	Empty box	0.113	0.059	0.174
	Water bottle	0.147	0.083	0.286

4 Inventory localization combining AOA measurement and RSS

Products inventory is an important activity in warehouse management. Some RFID-based inventory solutions have been reported to be applied in warehouse management [5, 29]. This section proposes an inventory localization approach which is compatible with the existing RFID inventory system. And the proposed method can efficiently improve the localization accuracy against multi-path.

4.1 AOA measurement and errors

The AOA can be measured by phase difference on an antenna pair [30]:

$$\theta = \sin^{-1}\left[\frac{\lambda}{2\pi L}(\Delta\varphi - \Delta\varphi_0)\right] \tag{4}$$

where $\Delta\varphi$ is the measured phase difference between the two antennas; $\Delta\varphi_0$ is the phase difference caused by the hardware of the reader, antennas, and connectors; L is the distance between the two antennas; λ is the wavelength of the carrier; θ is the angle from the tag to the antenna pair.

However, the AOA measurement is influenced by multi-path propagation. To verify this, an experiment was carried out. Antenna pairs were placed at 8 different positions to measure the AOA of 21 tagged items on a shelf, as illustrated in Fig. 11. Five antenna pairs were situated 1.5 m by the side of the shelf with heights from 0.33 m to 1.33 m. Three antenna pairs were set 1.5 m in the front. The shelf and products are shown in Fig. 12.

Statistics were made to analyze the relationship among AOA measurement errors with distance from tag to reader antenna, actual AOA and RSS. The antenna pairs were divided into two groups while antenna pairs 1−5 to be one group and 6−8 to be another.

The results are plotted in Fig. 13, in which some tags may be not detected by the reader and not plotted. From Figs. 13(a) and (b), there is no explicit relationship

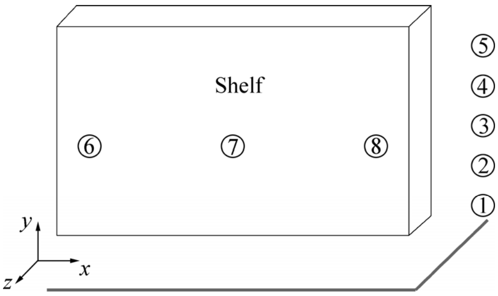

Fig. 11 Eight different positions for antenna pairs selected for analysis of AOA measurement errors

Fig. 12 Experimental environment

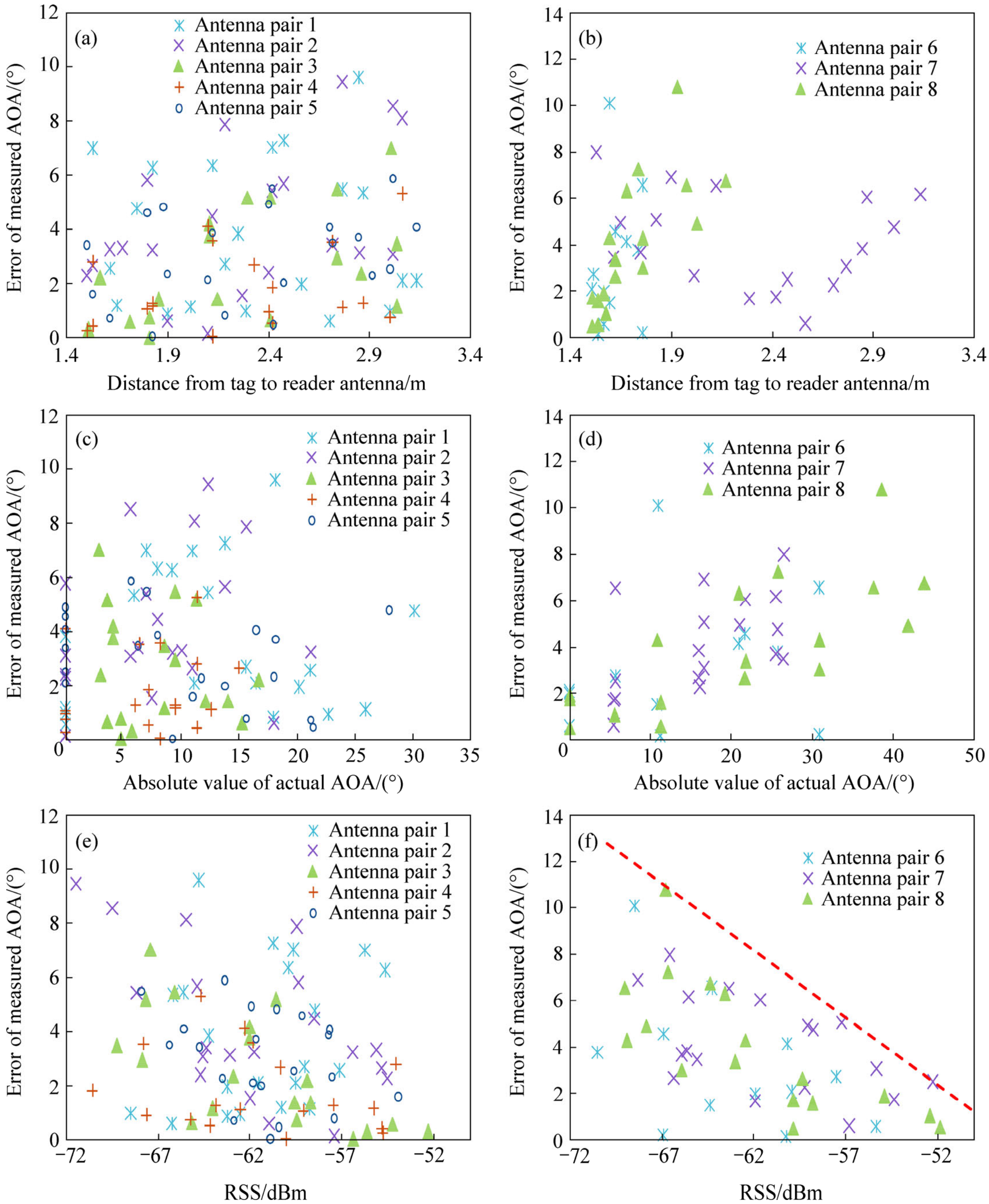

Fig. 13 Relationship between AOA measurement errors with distances (a, b), angles (c, d) and RSS (e, f)

between the localization error and the distance. As for the relationship between the actual AOA and the error, on antenna pairs 1−5 there is also no obvious regular pattern. On antenna pairs 6−8, the localization errors increase with the actual AOA, but the regularity is also imprecise. For RSS, an accurate pattern can be found between the RSS and localization error, especially on antenna pairs 6−8. When the RSS decreases, the localization error significantly increases. And all the points fall under a straight line which is marked red in the figure. In summary, two rules can be found from the experiment: the error distribution on antenna pairs which are in front of the shelf is more regular than the one by the side; there is a strong relationship between the RSS and the localization error. Low RSS may result in high AOA measurement errors.

As multi-path is the main factor which influences the AOA measurement, between the tag and the reader antenna, there is one line-of-sight (LOS) path, and several none-line-of-sight (NLOS) path, as illustrated in Fig. 14.

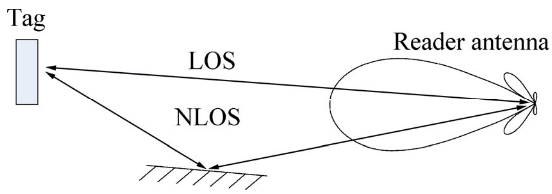

Fig. 14 UHF RFID multi-path channel model

The corresponding channel pulse response contains a direct LOS path of length $d_{\rm LOS}$ and M reflected path of length d_i.

$$h(t)=A_{\rm LOS}\cdot\delta(t-\frac{d_{\rm LOS}}{c_0})+\sum_{i=1}^{M}A_i\cdot\delta(t-\frac{d_i}{c_0}) \quad (5)$$

The channel attenuation is

$$\begin{cases} A_{\rm LOS}\propto(\dfrac{\lambda}{4\pi d_{\rm LOS}})^2\cdot G_{\rm LOS,reader}\cdot G_{\rm LOS,tag} \\ A_i\propto(\dfrac{\lambda}{4\pi d_i})^2\cdot G_{i,\rm reader}\cdot G_{i,\rm tag}\cdot \varGamma_i \end{cases} \quad (6)$$

where $G_{x,y}$ stands for the angle dependent antenna gain of device y in the direction of x; $\varGamma_i$ is the polarization dependent reflection coefficient of scatter i.

The two phasors are shown in Fig. 15. For antenna pairs 6−8, there is always a significant LOS path, and the amplitude of LOS signal is higher than the amplitude of NLOS signal. So, when the RSS is strong, the $A_{\rm LOS}$ has a high value which will lead to a smaller influence on the received signal phase by the multi-path.

Another reason lies in the phase measurement. In our system, the phase was measured by the baseband signal of the tag. Actually, both RSS and phase can be measured on IQ (in-phase and quadrature) plane:

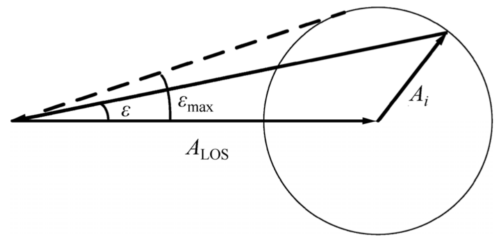

Fig. 15 Geometrical interpretation of phase error

$$\begin{cases} {\rm RSS}\propto\dfrac{I^2+Q^2}{z_0} \\ \varphi=\arctan(\dfrac{Q}{I}) \end{cases} \quad (7)$$

where z_0 is the input impedance of the receiver. When the RSS is strong, the baseband error will lead to less error in phase measurement.

4.2 Inventory localization approach

Now we can use the RSS to estimate the credibility of the localization result. The inventory localization system can be achieved by a mobile cart with antennas installed on it, as illustrated in Fig. 16. Two antenna pairs are used with each pair providing one AOA. Then the position of the product can be calculated, as shown in Fig. 17.

$$\begin{cases} x=x_{\rm a}-L\tan\theta_1\sqrt{\dfrac{1+\tan^2\theta_2}{1-\tan^2\theta_1\tan^2\theta_2}} \\ y=y_{\rm a}-L\tan\theta_2\sqrt{\dfrac{1+\tan^2\theta_1}{1-\tan^2\theta_1\tan^2\theta_2}} \end{cases} \quad (8)$$

where $(x_{\rm a}, y_{\rm a})$ denotes the position of antenna pair center.

The cart moves through the shelves and the reader performs inventory at several fixed inventory points. Then, each tag may get several localization results. The result with the highest RSS is treated as the final position of the tag.

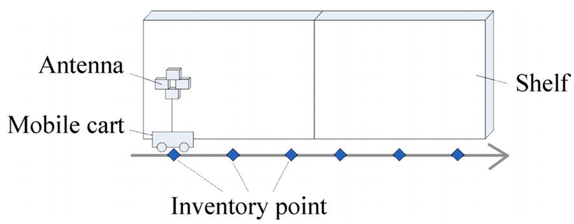

Fig. 16 Mobile inventory system

4.3 Experiments and results

The experimental environment was just the same as

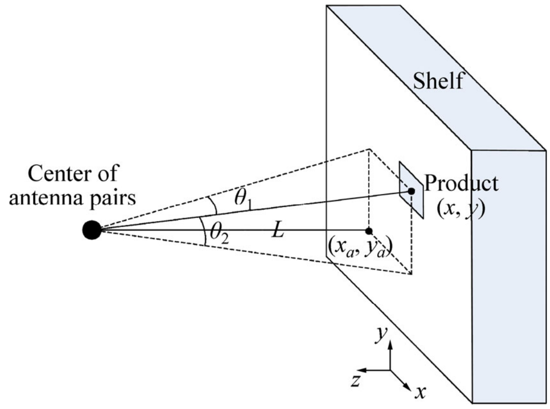

Fig. 17 Position calculation using two antenna pairs

Fig. 12. In the first experiment, the center of antenna pairs was set at the middle of the shelf and the localization was performed once. The results are shown in Fig. 18. The relationship between RSS and localization errors is plotted in Fig. 19.

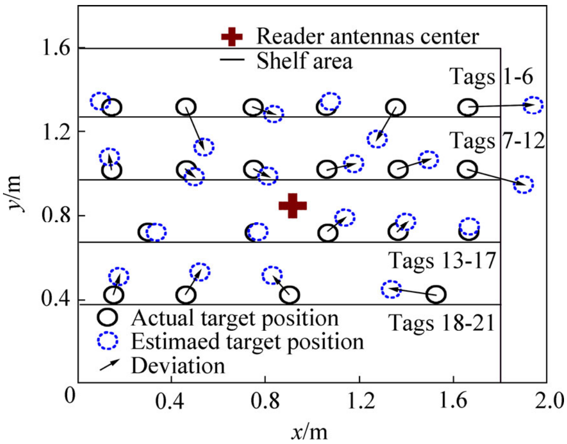

Fig. 18 Results of stationary localization

The second experiment was carried out as illustrated in Fig. 20. The antennas moved through the shelf, and executed inventory at three points. The distance between antennas and the shelf was 1.5 m. Each tag got three localization results at most, and the result with the highest RSS was treated as the final position of the tag. The results of mobile inventory system are plotted in Fig. 21. The mean error was 0.097 m. The max error was 0.153 m which was significantly improved compared with the stationary localization.

Table 2 shows the comparison between stationary localization and mobile inventory localization. The mobile inventory localization system is highly accurate

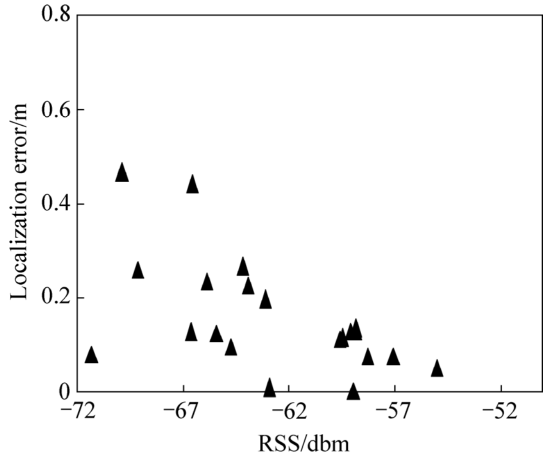

Fig. 19 Relationship between localization errors and RSS

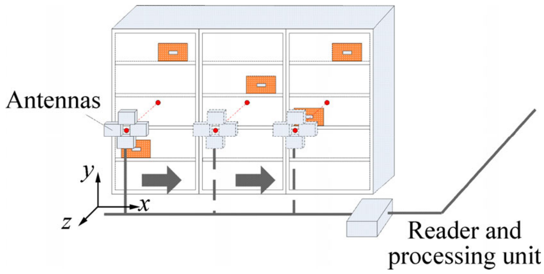

Fig. 20 Experiment illustration of mobile inventory system

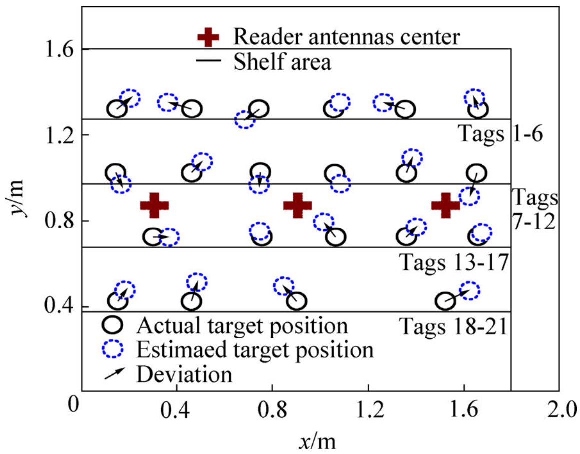

Fig. 21 Results of mobile inventory system

and robust as the mean error 0.097 m, standard deviation 0.035 m and maximum error 0.153 m. The mobile inventory localization system needs to move the reader antennas and perform interrogation several times. However, in a RFID-based automatic inventory system in warehouse management, for accessing all target tags, moving the reader antenna and performing interrogation several times is also necessary.

Table 2 Performance of inventory localization system

Localization	Measurement	Inventory point	Mean error/m	Standard deviation/m	Maximum error/m
Stationary localization	AOA	1	0.156	0.118	0.468
Mobile inventory localization	AOA and RSS	3	0.097	0.035	0.153

5 Conclusions

Products localization in warehouse management is investigated. Tag signal phase is utilized and localization approaches for both checking-in and inventory operations are proposed. For products checking-in, the LUPV approach is proposed. Experimental results show a 0.113 m mean error of localization. For inventory localization, the approach combining AOA and RSS is proposed. The RSS is proved to be a valid foundation to estimate the credibility of the AOA measurement against the multi-path. The experimental results show a 0.097 m mean error of localization. Moreover, the proposed approaches are compatible with the existing RFID based checking-in and inventory system. No requirement for any measurement modules to the existing RFID systems also makes this method useful.

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