An Improved HMFCW Algorithm for Ranging in RFID System

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Abstract. Since the measured phase is usually a wrapped phase during ranging, the phase-based ranging method needs to solve the ambiguity so as to obtain the true phase. HMFCW (heuristic multi-frequency continuous wave) algorithm provides the same tolerance of error for the observed phase of different frequencies. When the error of phase is within the tolerance and the range of ranging is less than the period, the phase error tolerance method can get the correct cycle number, and achieve a ranging accuracy of centimeter. However, when phase errors of some frequencies are large, HMFCW algorithm may have difficulty in solving the integer ambiguity, which leads to the decrease of ranging accuracy. In this paper, an improved HMFCW algorithm based on HMFCW algorithm is proposed. The improved HMFCW algorithm calculates the average value of the clustering phase results to eliminate the phases with large errors, and performs the cycle calculation to obtain the ranging value. Simulation results show that improved HMFCW algorithm can solve the problem of error in the cycle ambiguity solution caused by the point with large phase error effectively, and improve the ranging accuracy.

Keywords: Phase cycle ambiguity · Improved HMFCW algorithm · The point with large phase error · Phase error tolerance · Ranging

1 Introduction

With the development of radio frequency identification (RFID) technology, the energy required to activate the tag has become lower and lower, and the reading range of the reader has become larger. Researchers have gradually realized the importance of ultra-high frequency radio frequency identification (UHF RFID) ranging technology and have carried out related researches. UHF RFID ranging methods based on time of arrival (TOA), received signal strength (RSS), and phase of arrival (POA) have been developed recently [1]. The TOA-based ranging method requires strict synchronization of clock between devices, and the cost is relatively high. RSS-based ranging methods can be divided into model ranging method [2] and fingerprint ranging method [3]. However, RSS is greatly affected by the indoor environment and has poor stability, the accuracy of it is low usually. As for the ranging method based on the phase of arrival, the phase has the ambiguity of the cycle in the RFID system and cannot be used for ranging directly [4]. The current phase-based UHF RFID ranging system can be

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divided into two categories according to the scene: tag or antenna of reader in the ranging system move or the tag and reader antenna are stationary.

Many ranging systems with phase-based UHF RFID rely on the movement of the tag or antenna of reader to locate the tag. E. Di Giampaolo et al. installed the antenna of reader on the mobile robot, and locate the tag by fusing the information of phase in the tag and the mileage information of the robot [5]. A. Buffi et al. built a synthetic aperture array by moving objects on the conveyor belt, combined with the information of phase in the tags to locate the object [6]. Hong Chao of Huazhong University of Science and Technology installed the antenna of reader on the robot, and obtained data of phase in different positions with the help of the robot's movement, and obtained the true phase by using the ambiguity resolution algorithm based on shooting method. The final ranging accuracy is decimeter [7]. The ranging system that relies on the movement of the tag or antenna of reader can restore the true phase more accurately, and its ranging accuracy can achieve a ranging accuracy of decimeter. However, this type of system has certain requirements for the movement of the tag or antenna and cannot locate static target.

When the tag and antennas of reader are stationary, the phase difference of arrival (PDOA) method is used to solve the ambiguity commonly. The PDOA method is divided into two types mainly: Frequency Domain (FD) and Spatial Domain (SD) [8]. The FD-PDOA method refers to measuring the phase of tags under carriers with different frequencies, and using PDOA to calculate the distance between the tag and the reader. Li proposed a ranging algorithm based on multi-frequency carrier phase [9], which combined the Chinese remainder theorem on the basis of the difference of phase in dual-frequency to select a combination of frequency that is more conducive to solving the ambiguity and obtains a larger Non-ambiguous distance. The SD-PDOA method is to measure the phase of tag in multiple antennas at the same frequency, and solve the position of tag relative to the antenna through PDOA. Liu uses multiple antennas placed side by side to measure the phase of the tag, constructs a hyperbolic equation set through PDOA, and then obtains the target position by finding the intersection point of the hyperbola [10]. Compared with the RSS, the information of phase is more accurate and stable, and the ranging method based on PDOA has higher accuracy, which can achieve a ranging accuracy of meter or even the decimeter. In recent years, Yunfei Ma in Cornell proposed a method to expand the bandwidth of UHF RFID system [11], which created favorable conditions for solving ambiguity, and he proposed HMFCW (heuristic multi-frequency continuous-wave) on the basis of expanding bandwidth. The ambiguity solving algorithm achieves a ranging accuracy of centimeter, which improves the accuracy of UHF RFID ranging technology greatly. Nevertheless, when the error of phase at some frequencies is large, HMFCW algorithm may have the problem of solving the ambiguity, which causes the ranging accuracy to decrease.

In order to solve this problem, this paper conducts a more in-depth study on the basis of HMFCW algorithm, and proposes improved HMFCW algorithm, when the phases have excessive error, improved HMFCW algorithm can eliminates the influence of it and improves the accuracy of ranging. Simulation results show that when the phases contain points with large phase error, the cumulative probability of HMFCW algorithm within the range of 0−0.3 cm is 52.3%, while improved HMFCW algorithm is 71.3%. Experiment results also show the same conclusion.

The rest of this paper is organized as follows: Sect. 2 introduces the overall architecture of the RFID system; Sect. 3 introduces the theory of HMFCW algorithm; Sect. 4 gives a detailed description and analysis of the improved HMFCW algorithm, and simulation results are provided to demonstrate the effectiveness of the proposed algorithm; Finally, Sect. 5 summarizes the work of this paper.

2 Brief Review

2.1 RFID System Architecture

The RFID system proposed by this paper is shown in Fig. 1. The main functions of the reader are to communicate with tag and to be responsible for reading or writing information of tag [12]. The reader usually obtain the signal phase by method of I/Q signal complex demodulation [13]. The computer is the control center, which is used to issue relevant instructions to reader and set relevant parameters, store and process information of tag. The information of tag read by the reader can also be displayed in the computer [14]. The system consists of two kinds of transmitters and receiver. Transmitter 1 is an Impinj R420 reader to activate tag, and transmitter 2 and receiver are USRP devices to locate tag. Impinj transmits a continuous high-power radio frequency signal with frequency of f_1(902−928 MHz) to activate the tag. USRP transmits a low-power signal with frequency of f_2(750−930 MHz) by frequency hopping, and the step of frequency hopping is 10 MHz. Frequency hopping can expand the bandwidth of system. Other USRP receives the data whose frequency is f_2 returned from tag, and the data is used for ranging.

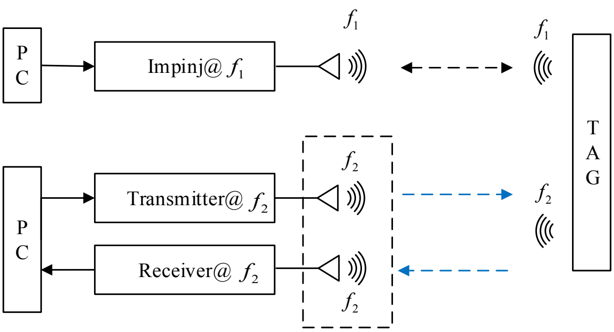


Fig. 1. RFID system architecture

After the signal sent by the USRP arrives at the tag, the tag modulates the stored ID information onto the signal and the signal reaches the receiver through backscattering. The receiver performs coherent demodulation on the received signal and demodulates the signal. Computer obtains the phase after relevant processing. The phase is determined by the sum of the distances from the USRP to the tag and the tag to the receiver.

Finally, the obtained phases at different frequencies are substituted into the ranging algorithm in the Matlab software to calculate the position of tag.

2.2 RFID Phase Ranging Theory and HMFCW Algorithm

When electromagnetic waves propagate in space, the energy gradually attenuates, and its phase also changes periodically. The distance can be estimated through the energy attenuation or change of phase, but the distance estimated by the energy attenuation will cause huge errors of ranging, so this section introduces the changing law of the phase in the electromagnetic wave propagation process, which provides the basis for the algorithm for solving the integer ambiguity.

The propagation speed of electromagnetic waves in the air is the speed of light c. Electromagnetic waves have two important properties: frequency f and wavelength λ. The relationship between them is $\lambda = c/f$. Electromagnetic waves propagate in all directions in a periodic oscillation manner. The phase will change 2π when the electromagnetic wave propagates for a distance of one wavelength in space. It can be seen that the true change of phase θ caused by the distance d *is*

$$\theta = 2\pi \frac{d}{\lambda} = 2\pi ft \tag{1}$$

The signal generated by the USRP is an electromagnetic wave. So other shifts of phase, except the change of phase caused by the distance, will be also added in during the propagation. The true change of phase from the USRP to the receiver through the tag is

$$\varphi = -w_c\tau + \varphi_S - \varphi_L + \varphi_T \tag{2}$$

where $w_c\tau$ is the change of phase caused by the distance of propagation, but it becomes a negative value during the demodulation process, $\varphi_S - \varphi_L$ is the initial difference of phase between the transmitted signal and the received signal, and φ_T is the offset of phase introduced by tag. Due to the periodicity of the sinusoidal signal, the phase of the tag measured by the receiver is not the true phase but a wrapped phase ϕ. The relationship between it and the true phase φ is

$$\phi = \varphi + 2n\pi \tag{3}$$

where n is the integer of cycles. The phase $\phi \in (-\pi, \pi]$ ϕ is called the observed phase, the difference between ϕ and the real phase φ is an integer multiple of 2π.

In the real change of phase φ, the distance-related part is only $w_c\tau$, so the influence of interference phase needs to be eliminated before ranging, $\varphi_S - \varphi_L$ and φ_T are fixed value under the same system, and can be eliminated by calibration. For the convenience of discussion, "observed phase" and "true phase" in the following both refer to the value after eliminating the fixed phase offset.

The frequency allocated to UHF RFID in China is very limited (920–925 MHz). So the phase difference of arrival in frequency domain (FD-PDOA) method will cause a large error when ranging. Yunfei Ma proposed a frequency hopping scheme to expand bandwidth [11], in which one USRP transmits a high-power signal to provide energy for the tag, meanwhile, other USRPs transmit low-power signals to achieve channel estimation by frequency hopping method. This program does not interfere with other electromagnetic communications and expand system bandwidth. The bandwidth of signals using frequency hopping can reach 220 MHz, creating a condition for solving the integer ambiguity.

The USRP obtains the phases at different frequencies f through frequency hopping, and the wavelengths of these frequencies are different, so the distance can be estimated by combining the phases of different frequencies. According to Eqs. (2) and (3), the relationship between RFID phase and distance is derived, and it can be expressed as:

$$\begin{cases} (\frac{\phi_1}{2\pi} + n_1) \times \lambda_1 = d \\ (\frac{\phi_2}{2\pi} + n_2) \times \lambda_2 = d \\ (\frac{\phi_i}{2\pi} + n_i) \times \lambda_i = d \\ \cdots \\ (\frac{\phi_n}{2\pi} + n_n) \times \lambda_n = d \end{cases} \tag{4}$$

where d represents the propagation distance of the signal, ϕ_i, n_i, λ_i represent the observed phase, the integer of cycles, and the wavelength of the frequency of f_i, and n_i is a non-negative integer. In the Eq. (4), n_i and d are unknown, ϕ_i and λ_i are known, $i = (1, 2, \ldots, n)$, and the Eq. (4) is an underdetermined equation, but only non-negative integers can be used in n_i, and the range of d is also limited, so that n_i and d can be solved.

In Fig. 2. Assuming that the reader obtains the observed phases at 4 different frequencies, the distance of the observed phase is obtained from $\phi_i/(2\pi) \times \lambda_i$, and it adds $0, 1, 2, \ldots, N_{\max}$ times wavelength to get multiple distance. There is a value very close to the actual distance, and the $N_{\max}$ is determined by the ranging range. Since the true distance is fixed, the distances each frequency closed to each other are clustered into one category, and the category with the smallest variance among the clustering results is selected to be the result of ranging. Literature [15] proposed HMFCW algorithm to solve the integer ambiguity. The algorithm provides the same error tolerance for the observed phase at different frequencies. The theory and specific steps of HMFCW integer ambiguity solution algorithm will be introduced in detail below.

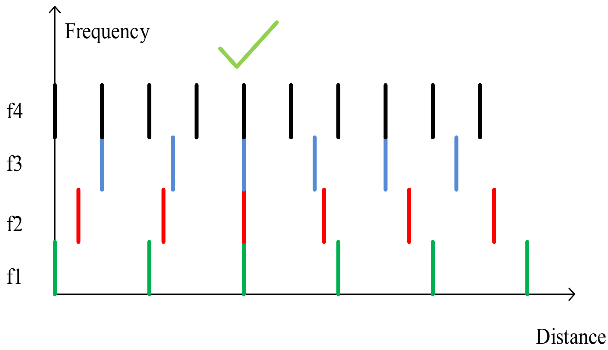


Fig. 2. Theory of solving the integer ambiguity

The numbers of cycle at each frequency constitutes an array of cycle. Among all the clustering results, the type closest to the true distance is considered as the correct cycle number. Other numbers of cycle are called wrong cycle number. In particular, the two numbers closest to the correct cycle number (one on each side) are called adjacent cycle number. HMFCW algorithm obtains the correct cycle number through correlation operations, thereby realizing ranging.

In order to introduce the parameter phase error, the estimated distance is expressed as

$$d^{(i)} = d + \frac{\Delta\phi_i}{2\pi} \times \lambda_i \tag{5}$$

where d represents the true distance and $\Delta\phi_i$ represents the observed phase error at frequency f_i. Assuming that the absolute value of the error of observed phase at all frequencies is less than $\Delta\phi$, the distances of any two frequencies are subtracted and substituted into Eqs. (4) and (5) to obtain

$$\begin{aligned} \left|d^{(i)} - d^{(k)}\right| &= \left|n_i' \times \lambda_i + \frac{\phi_i}{2\pi} \times \lambda_i - n_k' \times \lambda_k - \frac{\phi_k}{2\pi} \times \lambda_k\right| \\ &= \left|\frac{\Delta\phi_i}{2\pi} \times \lambda_i - \frac{\Delta\phi_\mathrm{k}}{2\pi} \times \lambda_k\right| < \frac{\Delta\phi}{2\pi} \times (\lambda_i + \lambda_k) \forall i, k \end{aligned} \tag{6}$$

where n_i' represents the actual cycle number. It is known that the correct cycle number satisfies the Eq. (6), but when the $\Delta\phi$ setting is too large, the wrong cycle number will also satisfy the Eq. (6). In order to distinguish the correct cycle number from multiple numbers of cycle and make $\Delta\phi$ as large as possible, $\Delta\phi$ are derived following.

Supposing there is another cycle number satisfying Eq. (6), then

$$-\Delta\phi < \frac{2\pi \times \left((n_i' + b_i) \times \lambda_i + \frac{\phi_i}{2\pi} \times \lambda_i - (n_k' + b_k) \times \lambda_k - \frac{\phi_k}{2\pi} \times \lambda_k\right)}{\lambda_i + \lambda_k} < \Delta\phi \qquad \forall i, k,\ \exists b_i, b_k,\ \sum\nolimits_i b_i^2 > 0 \tag{7}$$

By changing the form of Eqs. (6) and (7), we can get:

$$\frac{\pi \times |b_i \times \lambda_i - b_k \times \lambda_k|}{\lambda_i + \lambda_k} < \Delta\phi\ \forall i, k, \exists b_i, b_k,\ \sum\nolimits_i b_i^2 > 0 \tag{8}$$

If Eq. (8) deduces a contradiction, and according to proof by contradiction, Eq. (7) does not exist, then there will only be a correct cycle number. Since the gap between the distances of the adjacent cycle number is smallest than other number except the correct number, the unique solution can be guaranteed when the adjacent cycle number fails to pass the judgement (provided that there is enough frequency), so $b_i = 1$, $b_k = 1$, get

$$\Delta\phi_{\max} = \frac{\pi \times (f_{\max} - f_{\min})}{f_{\max} + f_{\min}} \tag{9}$$

where f_{max} represents the maximum frequency of frequency hopping signals, and f_{min} represents the minimum frequency. The equation above is the most reasonable value of $\Delta\phi$. It obtains the maximum value under the condition that the cycle number to be calculated is correct, and the value $\Delta\phi_{\max}$ is called the error tolerance.

Limiting the cycle number through the range of ranging, and judging the distance by one frequency with another, and getting the expression:

$$\begin{cases} 2\pi \times \dfrac{\left|n_i \times \lambda_i + \frac{\phi_i}{2\pi} \times \lambda_i - n_k \times \lambda_k - \frac{\phi_k}{2\pi} \times \lambda_k\right|}{(\lambda_i + \lambda_k)} < \Delta\phi\ \forall i, k \\ n_i \le \dfrac{R_{\max}}{\lambda_i}\ n_i \in N \end{cases} \tag{10}$$

where n_i represents the cycle number to be found, $\Delta\phi$ represents the judgement threshold, and its initial value is taken as $\Delta\phi_{\max}$, $R_{\max}$ represents the maximum distance of ranging, N represents a natural number.

Equation (9) expresses the relationship between error tolerance and frequency. Substituting the observed phase and its frequency into Eq. (10), the correct cycle numbers can be obtained when the error of observed phase at all frequencies is less than $\Delta\phi_{\max}$, then the ranging result can be acquired. However, the error of measured phase may exceed the error tolerance. In that case, the measure taken is to enlarge $\Delta\phi$ gradually until a cycle number passes. The accuracy of ranging can achieve a ranging accuracy of centimeter when getting the correct cycle number. When the phase error is bigger than the error tolerance, the result is mostly adjacent numbers of cycle, so the ranging accuracy is about at the decimeter.

To summarize HMFCW algorithm, the steps are as follows:

1. Add the distance of the observed phases to an integer multiple of the wavelength to obtain multiple distances, classify the distances that are close at each frequency into one category, and record the number of the cycle of each category.
2. Substitute various corresponding phase and cycle number into Eq. (10) for judgement, where the value of $\Delta\phi$ at the first judgement is $\Delta\phi_{\max}$.
3. If step 2) can get a cycle number, then go to step 4). If no cycle number passes, then the decision threshold $\Delta\phi$ will be enlarged by 1.02 times and return to step 2).
4. Obtain the distance at each frequency from the observed phase and the cycle number through the judgement, and use these distances to obtain the final ranging result.

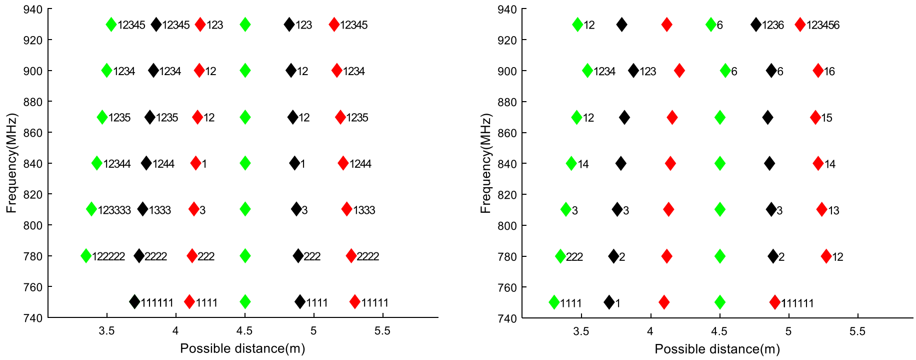
The ranging effect of HMFCW algorithm is related to the frequency of frequency hopping and bandwidth. After actual measurement, the RFID system built in this paper has good quality of signal in 750–930 MHz and can decode successfully. Therefore, the simulation and experiment are all within this range. At the same time, this paper uses equal interval frequency hopping.

3 Improved HMFCW Algorithm

The system changes the frequency by frequency hopping, collects the phase of the tag at the same position and different frequencies, and then substitutes the phase and its frequency into the error tolerance method to obtain the result of ranging. However, in the actual process of acquiring phase, the error of phase at certain frequencies may be too large, which is called the point with large phase error. If the point with large phase error is substituted into HMFCW algorithm, it may cause large error of ranging in the solving integer ambiguity.

In order to explain the impact of the point with large phase error on solving the integer ambiguity better, the situation of solving the integer ambiguity before and after adding the point with large phase error is shown by Fig. 3. The parameters used for drawing are as follows: the range of frequency is from 750 MHz to 930 MHz, 7 frequencies at equal intervals in this range, the distance is 4.5 m, and the phase error is taking 0.8 radians and −1.2 radians on 900 MHz, 930 MHz respectively.

Substituting the true phase and its frequency to get Fig. 3(a), and substituting the phase of points with large error phase to get the Fig. 3(b). A column of points with the same color are a class of clustering result in the figure. The result is shown by Matlab. For example, the third clustering result in Fig. 3(a) is marked with “3” at 810 MHz and 930 MHz, which means that these two points cannot pass the judgement at the same time. The mark is “3” because the smaller frequency (810 MHz) is the third frequency in array of frequencies when all frequencies are arranged from small to large. All the judgements are indicated by marks. In Fig. 3(a), only the fourth class of clustering result has no mark, indicating that the fourth class of clustering result is passed the decision of Eq. (10). This result of ranging is consistent with the true distance. In Fig. 3 (b), the phase errors at 900 MHz and 930 MHz are relatively large. The clustering results of the true distance cannot pass the judgement at these two frequencies, while the adjacent clustering results (the third class) passed. So the final result of ranging is one wavelength smaller than the true distance. The results in figure show that the point with large phase error may cause the correct cycle number to fail to pass the judgement, and the adjacent cycle number can pass the judgement because its difference of distance is smaller, which causes the ranging error to become larger. Therefore, it is necessary to process the points with large phase error.



(a) No point with large phase error (b) Contains points with large phase error

Fig. 3. The influence of the point with large phase error on solving the integer ambiguity

In the correct cycle number, the point with larger phase error will cause the distance to differ greatly from the mean value of the clustering result, so the point with large phase error can be filtered out by the method of averaging. However, if too many frequencies are filtered out, the error margin will be reduced, resulting in two or more ranging results appearing at the same time. If too few frequencies are filtered out, the point with large phase error cannot be filtered out completely, and the error of ranging is still large. To solve these problems, this paper proposes an improved HMFCW algorithm based on the phase error tolerance method: setting an initial value for the critical value of magnification of error tolerance at the beginning, if the magnification of error tolerance exceeds the certain critical value, the phase point with the largest phase error is removed and the remaining distances are judged. This process iterates until the clustering result passes the threshold. The algorithm calculates the ratio of the points with large phase error in the measured phase first generally, and then adjusts the critical value to ensure that the ratio of the filtered phase in the algorithm is close to this value. The pseudocode of improved HMFCW algorithm is shown in the Table 1 shown.

Table 1. The pseudocode of improved HMFCW algorithm

Input: $(f_1, f_2, \ldots f_m)$, $(\phi_1, \phi_2, \ldots \phi_m)$, $R_{\max}$, $bound$;
// $(f_1, f_2, \ldots f_m)$: Frequency
// $(\phi_1, \phi_2, \ldots \phi_m)$: Measurement phase
// $R_{\max}$: Maximum ranging range
// $bound$: Critical value of error tolerance
Output: Distance;

$\phi_{\max} = \pi \dfrac{f_{\max} - f_{\min}}{f_{\max} + f_{\min}}$, $\phi_{\max}' = \phi_{\max}$;
// Calculate the error tolerance, and the amplified error tolerance is $\phi_{\max}'$
$\lambda = c / f$;
// Calculate wavelength of each frequency
$N_{\max} = \dfrac{R_{\max}}{\lambda_m} + 1$;
// Calculate the maximum integer of cycle
for $n_m = 0 : N_{\max}$
$d_{temp} = n_m \times \lambda_m + \dfrac{\phi_m}{2\pi} \times \lambda_m$
for $i = 1 : m-1$
$n_i = round\left(\dfrac{d_{temp} - \dfrac{\phi_i}{2\pi} \times \lambda_i}{\lambda_i} \right)$;
// Round is a rounding function, clustering the distances under different frequencies
end for
end for
while (temp) do
if $\phi_{\max}' - \phi_{\max} > bound$
$[f, \phi] = \text{update}(f, \phi)$;
// Remove the farthest value from the clustering result
$\phi_{\max} = \phi_{\max}'$;
// Update the amplified value of the error tolerance
end if
if $2\pi \times \dfrac{\left| n_i \times \lambda_i + \dfrac{\phi_i}{2\pi} \times \lambda_i - n_k \times \lambda_k - \dfrac{\phi_k}{2\pi} \times \lambda_k \right|}{(\lambda_i + \lambda_k)} < \phi_{\max}' \quad \forall i, k$
$d = \dfrac{1}{m} \sum_{i=1}^{m} n_i \times \lambda_i + \dfrac{\phi_i}{2\pi} \times \lambda_i$;
//Calculate the mean value and use it as the final result

(*continued*)

Table 1. (*continued*)

$temp = 0$;
//The end of cycle flag
else
$\phi_{\max}' = \phi_{\max} \times ampli$
//Enlargement decision threshold
end if
end while
$ratio = \dfrac{length(f)}{m}$
//Record frequency utilization

4 Simulation and Experiment Results

4.1 Simulation Results

In the phase-based UHF RFID tag ranging system, the PDOA-based method is usually used to solving ambiguity of phase. Considering that this paper uses frequency hopping technology to expand the bandwidth, it is better to replace the frequency in the FD-PDOA method with the maximum and minimum frequencies of the frequency hopping to increase the bandwidth, improved method is named WB-PDOA. This paper will use WB-PDOA method and improved HMFCW algorithm for comparison.

In order to test the ranging accuracy of these algorithm, a multipath channel model is constructed using Matlab. The channel impulse response can be expressed as:

$$h(t) = \sum_{i=1}^{N} a_i \delta(t - t_i) \tag{11}$$

where a_i and t_i are the amplitude and delay of the i path respectively, and N represents the number of paths. The statistical characteristics of these parameters obey a certain probability distribution. Generating the amplitude of each path from the Rice distribution, setting the amplitude of direct path is 3 times larger the mean value of amplitude of multipath, and generating the arrival time interval of multipath from the exponential distribution to get the delay of each path. The average arrival time interval of the path is 10 ns [16].

Obtaining the phase of all frequencies through this model. The phase at each frequency has a 15% probability of being replaced with a point with large phase error to simulate the actual receiving phase. The error of the point with large phase error is within (0.5, 2) radians that obey uniform distribution. Performing 1000 times of simulation with or without points with large phase error, calculating the phase error at a frequency of 900 MHz, and obtaining the cumulative distribution function of the phase error as shown in Fig. 4. It can be seen from the figure that the maximum phase error of the phase generated by the multipath model is about 1 rad. In the case of points with large phase error, the maximum phase error reaches 2 rad, and 10% of the phase error is distributed in the range of (1, 2).

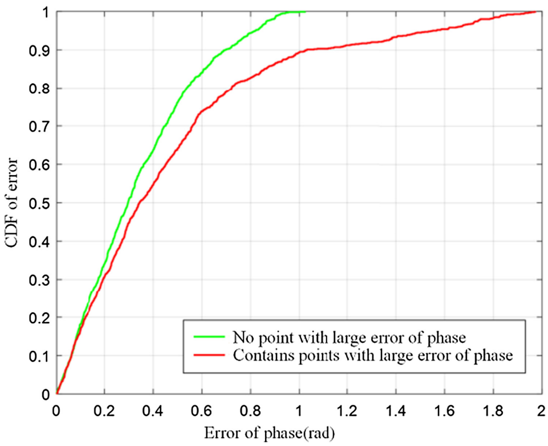
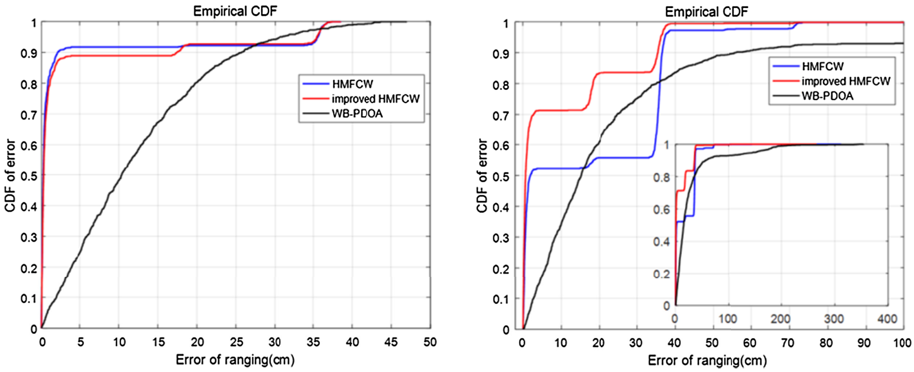


Fig. 4. Cumulative probability distribution of phase error

In the two cases above, calculating the ranging error of improved HMFCW algorithm. The juxtaposed algorithms are WB-PDOA algorithm and HMFCW algorithm. It can be seen from the Fig. 5 that when there is no point with large phase error, the improved HMFCW algorithm and the HMFCW algorithm have similar ranging errors, and the maximum error of both algorithms does not exceed 38.5 cm. The maximum error of the WB-PDOA algorithm is 47.2 cm, and its ranging error is larger than the improved HMFCW algorithm and the HMFCW algorithm. When there are points with large phase error, the improved HMFCW algorithm has a higher accuracy than HMFCW algorithm, and the maximum error of both algorithms does not exceed 73.3 cm. The cumulative probability of improved HMFCW algorithm is 18.7% higher than HMFCW algorithm when the error of ranging is within the range of (0, 3) cm, which shows that improved HMFCW algorithm can indeed eliminate the influence of points with large phase error, while the ranging error of the WB-PDOA algorithm is still larger than the improved HMFCW algorithm and the HMFCW algorithm.

Comparing Fig. 5(a) with Fig. 5(b), we can see that the cumulative probability of HMFCW algorithm within 0−0.3 cm is 52.3% with points with large phase error, and the improved HMFCW algorithm is 71.3%, which shows that the points with large phase error reduce the correctness of HMFCW algorithm significantly, and improved HMFCW algorithm can be more effective to eliminate the influence of point with large phase error. In addition, the cumulative probability of improved HMFCW algorithm in Fig. 5(b) increases significantly when the ranging error is 16−20 cm. This is because the algorithm may lead to the consequences that the correct number and adjacent cycle number passing through judgement simultaneously after eliminating points with large phase error. And the error will be about half a wavelength after taking the average of the two clustering results.



(a) No point with large phase error (b) Contains points with large phase error

Fig. 5. Comparison of ranging error in the two cases

4.2 Measurement Results

The algorithm is verified through experiments, and the place of experiment is shown in Fig. 6.

Fig. 6. Place of experiment

The antennas of USRP and Impinj are fixed on a wall of 3.1 m high, 3 receivers are placed side by side, and the height of it is 1.5 m. All USRPs are close to wall. The heights of tag and receiver are same. The yellow marks in the Fig. 6 are test points. The test points are marked with different numbers, and they are arranged at equal interval. The interval between two adjacent points is 0.5 m. 25 positions are tested. The height of the tag remains unchanged when the position of tag is changed.

HMFCW algorithm and improved HMFCW algorithm are used to complete this experiment. The performance of the two algorithms is evaluated by the error of ranging. In the experiment, the measured phase at most frequencies is close to the theoretical phase, and the difference of phase is within 0.3 radians. While at a few frequencies, measured phases are far from the theoretical phase, and the difference of phase exceeds 0.7 radians. That's say there are points with large phase error in the measured phase.

By substituting the measured phase into HMFCW algorithm and improved HMFCW algorithm, the ranging can be obtained. The results of ranging in the first 10 positions of antenna 1 are shown in Table 2. And ranging errors of each antenna at the 25 positions are shown in Fig. 7.

Table 2. Ranging results of the first 10 positions of antenna 1

Number of position	True distance (cm)	Result of HMFCW (cm)	Error of HMFCW (cm)	Result of Improved HMFCW (cm)	Error of Improved HMFCW (cm)
1	338.6	338.5	0.1	338.8	0.2
2	340.3	379.5	39.2	324.1	16.2
3	364.8	360.4	4.4	360.4	4.4
4	419.8	420.3	0.5	420.3	0.5
5	483.3	521.5	38.2	521.5	38.2
6	417.2	415.3	1.9	415.3	1.9
7	418.0	456.1	38.1	455.8	37.8
8	442.3	443.3	1	443.6	1.3
9	486.9	450.9	36	468.7	18.2
10	543.9	544.0	0.1	543.6	0.3

By observing the ranging results in Fig. 7, it can be found that the ranging error of improved HMFCW algorithm is concentrated in half of one wavelength. This is because the ranging error is mainly determined by the cycle number. Improved HMFCW algorithm removes the frequencies with the points of large phase error, which may lead to only the correct cycle numbers and the adjacent cycle number can pass the judgement. So the errors are concentrated in the half of one wavelength. When the ranging error of HMFCW algorithm is about one wavelength, improved HMFCW algorithm improves about half of the situation; when the consequence of HMFCW algorithm is correct, improved HMFCW algorithm can also be correct, two algorithms can remain consistent at this situation.

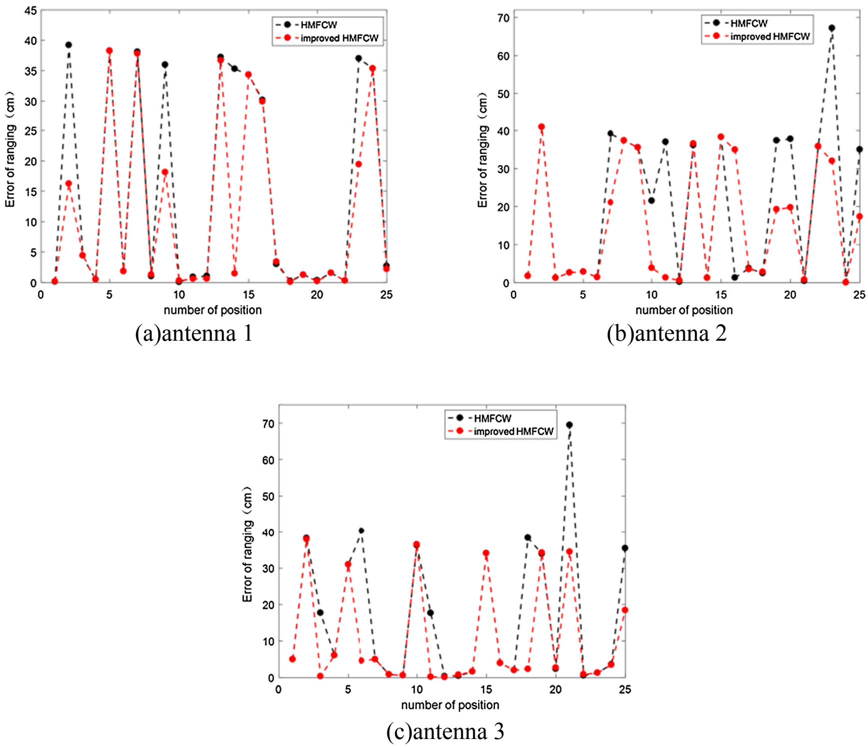


Fig. 7. Ranging error of each antenna

5 Conclusion

This paper proposes improved HMFCW algorithm to solve the problem of points with large phase error. Improved HMFCW algorithm calculates the mean value of the clustering results, then eliminate the phase with large error, and solve the integer ambiguity to obtain the consequence of ranging. Simulation results show that when the phases contain points with large phase error, the cumulative probability of HMFCW algorithm within the range of 0–0.3 cm is 52.3%, while improved HMFCW algorithm is 71.3%. Experiment results also show the same conclusion. It means that improved HMFCW algorithm can eliminate the influence of points with large phase error effectively and improve the ranging accuracy.

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