

MULTI-phase: A passive RFID positioning system based on multi-frequency phase difference

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Abstract. Accurate and rapid indoor positioning is essential for realizing the Internet of Things. Although satellite-based positioning works well outdoors, it often fails indoors due to signal blockage. Radio Frequency Identification (RFID) positioning technology has attracted attention due to its low cost, ease of deployment, and contactless operation. However, traditional methods based on Received Signal Strength Indicator (RSSI) are vulnerable to environmental interference, reducing accuracy. This paper proposes a passive RFID indoor positioning method that uses multi-frequency phase differences ranging. A Gauss-Kalman filter is applied to reduce the influence of environmental noise on phase data. A multi-frequency phase difference distance model is established, and the Chinese Remainder Theorem with a closed-form solution is used to solve phase ambiguity. Finally, a weighted Levenberg-Marquardt algorithm refines the target position, improving convergence and accuracy. Experiments conducted in different indoor environments demonstrate that the proposed method achieves an average positioning error of 0.38 m and a maximum error of 0.5 m, meeting the requirements of indoor positioning applications.

Keywords: Phase error, Phase difference ranging, Chinese remainder theorem, Weighted LM.

1 Introduction

Navigation and positioning technologies are extensively applied across various domains, including entertainment, transportation, healthcare, and emergency services [1]. Despite advancements in positioning technologies, indoor localization remains a challenge due to the inability of satellite signals to penetrate indoor structures effectively. Indoor environments pose a more complex signal propagation challenge, with wireless signals significantly weakened by multipath effects. This complexity makes precise indoor localization a difficult task. Research progress has given rise to various indoor positioning technologies, such as Zigbee, UWB, and WiFi [2–4]. Zigbee is user-friendly and cost-effective, yet it necessitates a denser network for improved communication. UWB offers superior precision but at the expense of more intricate hardware and higher expenses. WiFi, renowned for its broad coverage and diverse uses, is prone to interference from unidentified electromagnetic sources. Recently, Radio Frequency Identification (RFID) has gained popularity due to its cost-effectiveness and adaptability, being widely employed in sectors such as

industrial healthcare, logistics, and automation [5–7]. Traditional RFID positioning utilizes signal backscattering to activate tags for area localization; however, this approach lacks the necessary precision for intelligent applications. This research aims to harness the multi-frequency potential of RFID to create a new positioning method that achieves high-precision localization.

RFID positioning technology leverages the transmission of radio signals between readers and tags to collect information such as the tag's EPC number, Received Signal Strength Indication (RSSI), and phase. Given the correlation between RSSI and distance, the University of Washington developed the SpotON system in 2000 [8], which enables ranging and positioning by establishing a model linking RSSI to distance. Building on this, Yang *et al.* [9] incorporated Kalman filtering into the data processing, significantly enhancing the accuracy of the positioning.

Researchers have created RFID fingerprint databases in advance, using the unique characteristics of RFID signals [10–12]. They compare the information parameters of tags to be located with this database to determine their coordinates. The Hong Kong University of Science and Technology and Michigan State University introduced the

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LANDMARC positioning system [13], which identifies the best location by comparing the RSSI values of reference and unknown tags. However, this approach requires deploying many reference tags, which can lead to interference. In response, Zhao and colleagues developed the VIRE system [14], employing linear interpolation to decrease the number of reference tags and reduce costs. However, the RSSI values of virtual tags often differ significantly from real-world conditions.

Phase-based positioning methods are increasingly studied due to the phase's sensitivity to distance. However, the phase's periodic variation with distance introduces cycle ambiguity, preventing direct distance measurement from phase values. Rigall *et al.* introduced AOA-hyperbolas for positioning [15], and Azzouzi *et al.* used AOA-antenna arrays [16], both effectively avoiding phase ambiguity and enhancing accuracy. These methods, though, require multiple antennas and are subject to triangular constraints [17]. Liu *et al.* proposed a ranging method using dual-frequency carriers, calculating distance from phase differences at two frequencies [18]. This extends the distance, causing cycle ambiguity, but has lower bandwidth efficiency.

The combination of multi-frequency phase-difference ranging with a closed-form Chinese Remainder Theorem (CRT) solution, which directly addresses two major problems in passive RFID positioning: phase ambiguity and interference from environmental noise. While previous methods typically either employ single-frequency phases or use interpolation or iterative algorithms, our approach utilizes multiple carrier frequencies to construct a set of congruences and then solves them efficiently with closed-form CRT. This significantly enhances robustness against interference and avoids convergence problems often encountered by iterative methods when the initial estimates are poor. Furthermore, this closed-form solution reduces computational complexity, thereby making it more suitable for real-time and large-scale RFID applications. This combination sets our method distinctly apart from previous works, yielding higher accuracy, greater robustness, and lower computational latency.

The main contributions of this research are as follows:

1. Analyzing the principles of carrier phase acquisition and their influencing factors. To enhance the reliability of phase data, we apply Gaussian-Kalman filtering to reduce systematic and random interference.
2. A ranging method based on multi-frequency carrier phase differences is proposed. The phases at multiple frequencies are used to construct a set of congruences.
3. To solve the phase ambiguity gracefully, we apply a closed-form Chinese Remainder Theorem (CRT) solution instead of iterative methods. This approach avoids convergence issues stemming from poor initial estimates and reduces computational complexity.
4. A weighted Levenberg-Marquardt algorithm is introduced to combine the ranging information and produce robust and accurate tag location estimates.

The structure of the remaining sections is as follows. Section 2 introduces the origins and impacts of phase-related errors. Section 3 details the localization methodology,

encompassing phase error reduction techniques, a distance model derived from multi-frequency phase differences, a closed-form solution using the Chinese Remainder Theorem for distance calculations, and a weighted Levenberg-Marquardt algorithm for position estimation. Section 4 reports on the positioning experiments and their analysis. The final section concludes with the study and outlines future research directions.

2 Preliminaries

2.1 Phase Ambiguity

Electromagnetic waves propagate between the reader and the tag. Suppose the distance between the reader and the tag is d . The reader initially transmits a carrier wave with a frequency of f . Upon activation, the tag backscatters the signal, which the reader receives and measures a phase shift. During this process, the signal travels a distance of $2d$ and takes a time of t to propagate. This leads to the following relationship:

$$2d = t \cdot c. \quad (1)$$

The phase is:

$$\varphi = 2\pi ft. \quad (2)$$

By combining these equations, we establish the relationship between phase and distance as:

$$d = \frac{c\varphi}{4\pi f}. \quad (3)$$

However, due to the cyclical nature of the phase, which always falls within the range of 0 to 2π , a phase ambiguity arises when the signal's travel distance exceeds one wavelength. Consequently, if the measured phase at a specific time is φ , the actual phase could be $\varphi + 2n\pi$, where n represents the number of ambiguous cycles. This ambiguity cannot be resolved from the measurement alone. Therefore, our equation (3) should be modified to account for this ambiguity:

$$d = \frac{\lambda n}{2} + \frac{\lambda \varphi}{4\pi}. \quad (4)$$

In ultra-high-frequency RFID positioning systems, the maximum unambiguous distance is limited to a few dozen centimeters, which is insufficient for practical applications. Although reducing the signal frequency can extend the maximum unambiguous distance, it often leads to a decrease in positioning accuracy and stability. Therefore, careful analysis is required to balance the maximum unambiguous distance with the precision of phase-based positioning methods. To overcome the issue of phase ambiguity, this study primarily focuses on leveraging the multi-frequency carrier properties of RFID technology.

2.2 Phase error

In an ideal situation, phase data can be directly used for subsequent distance measurement and positioning. However, in practical positioning environments, due to

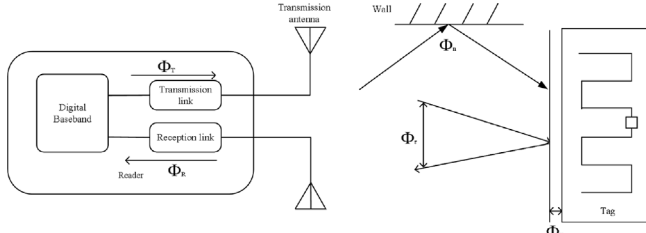


Figure 1. Diagram of phase change in signal propagation process.

the presence of phase errors, the phase information obtained by the reader's receiving end cannot be directly used for distance measurement. One of the key factors in utilizing phase information for distance measurement is the accuracy and stability of the phase data. Therefore, it is necessary to analyze the various causes of phase errors and propose methods for error suppression.

For passive ultra-high frequency RFID positioning systems, after the reader and tags complete bidirectional communication, the information received by the reader after demodulation includes the EPC number, RSSI, phase, frequency, and other relevant data. At this point, the observed value phase is the superposition of the phases from various components. The phase changes introduced at each stage are illustrated in Figure 1, specifically encompassing the following aspects:

$$\varphi = (\varphi_\tau + \varphi_0 + \varphi_{L0} + \varphi_T + \varphi_R + \varphi_{\text{Tag}} + \varphi_n) \bmod 2\pi. \quad (5)$$

Among these, φ_τ represents the cumulative phase shift introduced by the propagation distance of the transmitted carrier signal in space, which corresponds to the useful phase offset caused by the actual distance between the tag and the reader. φ_0 denotes the initial phase offset of the transmitted carrier signal, while φ_{L0} indicates the initial phase offset of the locally received signal. φ_T and φ_R refer to the phase errors introduced by the transmission and reception links, respectively. φ_{Tag} signifies the phase error introduced by the tag modulation, and φ_n represents the phase offset caused by environmental noise. The phase data collected by the experimental system's reader can only vary within the range of $[0, 2\pi)$, resulting in a 2π periodic ambiguity between the collected phase values and the actual phase values. This ambiguity arises from the periodic nature of the carrier signal, necessitating a phase unwrapping process before distance measurement [19].

3 Methods

Figure 2 illustrates the sequential steps involved in our positioning algorithm. First, data collection occurs as the RFID reader transmits carrier waves and receives backscattered signals from the RFID tags. Next, phase error suppression is carried out, where the acquired phase data undergoes a Gauss-Kalman filtering process to mitigate the effects of noise and environmental fluctuations, resulting in more accurate phase measurements. The filtered phase data is

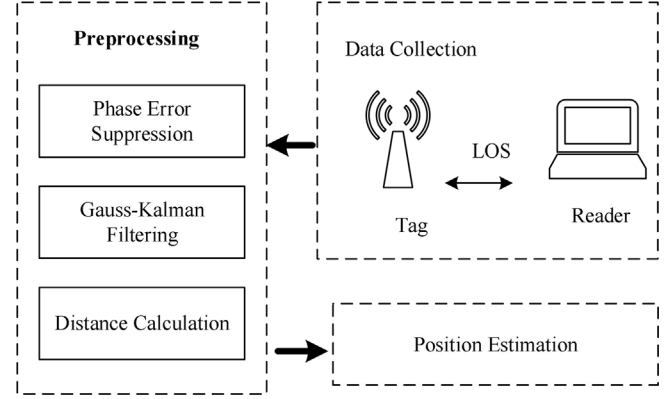


Figure 2. Location algorithm flow chart.

then analyzed through multi-frequency phase difference measurement, employing a multi-frequency carrier phase difference model that utilizes the Chinese Remainder Theorem to resolve phase ambiguities and calculate the distances between the reader and the tags. Following this, the distances obtained from multiple tags are computed and input into the positioning algorithm. Finally, the position estimation step employs the weighted Levenberg-Marquardt method to refine the position coordinates of the reader based on its distances to the tags, ultimately achieving the final position estimate.

3.1 Phase Error Suppression

It can be seen from the above that directly using phase observations for distance measurement and positioning results in significant errors. Therefore, it is necessary to eliminate the phase errors introduced by various components to enhance phase accuracy.

In a passive ultra-high-frequency RFID positioning system, the RFID reader uses the same local oscillator module. Therefore, the initial phase offset φ_0 of the transmitted signal and the initial phase offset φ_{L0} of the received signal are equal in magnitude but opposite in direction, allowing them to cancel each other out.

Typically, φ_T and φ_R denote the phase error introduced by the transmitter and receiver links, respectively, and φ_{Tag} is the phase error introduced by the label modulation. These errors can be mitigated using either the reference tag calibration method or the direct cable correction method. In this study, the reference tag calibration method is preferred for eliminating the errors associated with φ_T , φ_R , and φ_{Tag} . This method involves selecting a known tag position as a reference point, where the distance d between the tag and the reader antenna is predetermined. The phase at this specific reference point is measured.

$$\varphi = \varphi_d + \varphi_T + \varphi_R + \varphi_{\text{Tag}}. \quad (6)$$

By using the distance d between the tag and the reader antenna at this moment, the phase shift caused by the signal's transmission through space can be calculated using the formula:

$$\varphi_d = \text{mod}\left(\frac{4\pi fd}{c}, 2\pi\right). \quad (7)$$

By subtracting the two equations mentioned above, we can obtain the phase errors introduced by the transmission link, reception link, and label modulation. Record and save this data; after obtaining the measured phase from the actual experiment, subtract this reference value to achieve the elimination of the desired phase discrepancies.

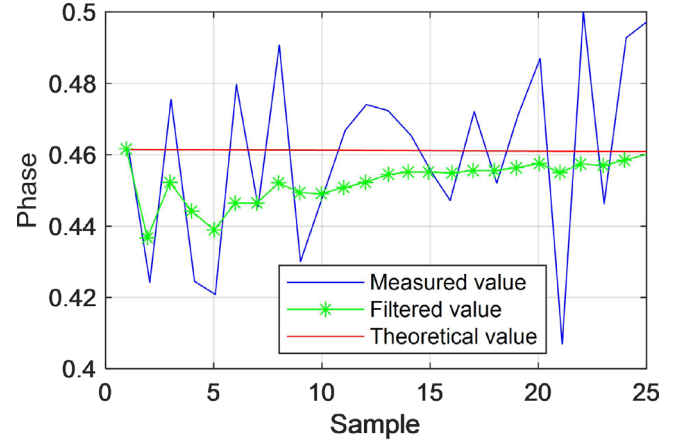
3.2 Gauss-Kalman Filtering

In practical positioning environments, the RFID reader-tag ranging positioning model utilizes phase data for distance measurement. After addressing phase errors introduced by the system, the acquired phase data remains susceptible to noise, leading to deviations from the actual values. To mitigate noise interference and enhance the accuracy of the phase acquisition process, this study employs filtering techniques. Initially, Gaussian filtering is applied to the acquired phase information, effectively removing phase data that significantly deviates from the expected values while preserving most data close to the true phase. However, Gaussian filtering alone is insufficient to entirely eliminate the impact of errors. To further refine the phase data used for ranging, the Kalman Filter method with the data retained is integrated after Gaussian filtering. This combined approach yields phase data that is closer to the actual values, thereby facilitating higher precision in subsequent ranging and positioning tasks.

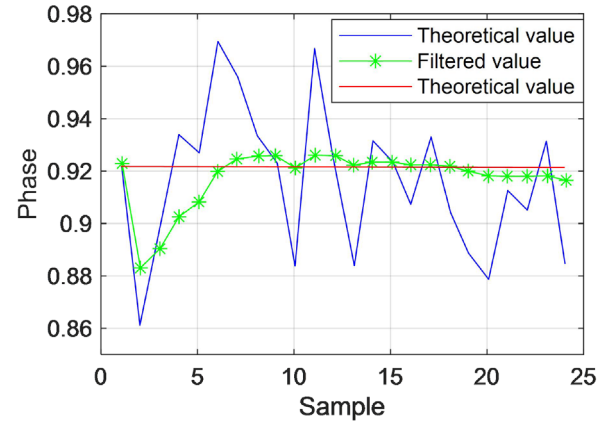
Experiments were conducted with the reader operating at a constant frequency of 920 MHz. The reader was placed at two distinct distances from the tags: 0.5 meters and 1.5 meters. Multiple samples of phase values for a single tag were acquired at these distances. A subset of this data was then processed using an optimized Gauss-Kalman filtering technique, and the results were compared against theoretical values, as illustrated in Figure 3. The figure demonstrates that after applying the filter to the phase values obtained at varying reader-tag distances, the fluctuations in the phase data were significantly reduced compared to the direct measurements. Additionally, the phase deviation was notably diminished, effectively mitigating the noise impact on phase measurements.

3.3 Multifrequency phase difference ranging model

Ultra-high frequency RFID readers can send carrier signals at different frequencies through frequency hopping within their working frequency band, and the phase values at each frequency can be measured at the receiving end. Now, assuming the ultra-high frequency RFID reader sends carrier signals at multiple different frequencies, with frequencies and satisfy $f_1 < f_2 < \dots < f_n$. Correspondingly, the phase values obtained are $\varphi_1, \varphi_2, \dots, \varphi_N$. As the phase can be affected by noise and other interference, the obtained phase is represented by $\Delta\phi_i$ ($i = 1, 2, \dots, N$) will still contain noise. Therefore, the received phase can be expressed as the sum of real phase and phase noise: $\varphi_i = \phi_i + \Delta\phi_i$. By combining the frequencies and corresponding phases of multiple carrier frequencies, the following system of equations can be obtained:



(a) 0.5m



(b) 1.5m

Figure 3. Gauss-Kalman filtering at different distances.

$$\begin{cases} \phi_1 + \Delta\phi_1 + 2n_1\pi = \frac{4\pi df_1}{c} \\ \phi_2 + \Delta\phi_2 + 2n_2\pi = \frac{4\pi df_2}{c} \\ \dots \\ \phi_N + \Delta\phi_N + 2n_N\pi = \frac{4\pi df_N}{c} \end{cases} \quad (8)$$

where n_i and $\Delta\phi_i$ ($i = 1, 2, \dots, N$) represents the number of phase ambiguity periods and the interference error of phase measurement at the i -th frequency, respectively. By subtracting adjacent equations from each other in this equation set, a new set of equations can be obtained as follows:

$$\begin{cases} (\phi_2 - \phi_1) + (\Delta\phi_2 - \Delta\phi_1) + 2(n_2 - n_1)\pi = \frac{4\pi d(f_2 - f_1)}{c} \\ (\phi_3 - \phi_2) + (\Delta\phi_3 - \Delta\phi_2) + 2(n_3 - n_2)\pi = \frac{4\pi d(f_3 - f_2)}{c} \\ \dots \\ (\phi_N - \phi_{N-1}) + (\Delta\phi_N - \Delta\phi_{N-1}) + 2(n_N - n_{N-1})\pi = \frac{4\pi d(f_N - f_{N-1})}{c} \end{cases} \quad (9)$$

Perform column transposition on the system of equations (9), resulting in the following system of equations:

$$\begin{cases} d = \frac{c(\phi_2 - \phi_1)}{4\pi(f_2 - f_1)} + \frac{c(\Delta\phi_2 - \Delta\phi_1)}{4\pi(f_2 - f_1)} + (n_2 - n_1) \frac{c}{2(f_2 - f_1)} \\ d = \frac{c(\phi_3 - \phi_2)}{4\pi(f_3 - f_2)} + \frac{c(\Delta\phi_3 - \Delta\phi_2)}{4\pi(f_3 - f_2)} + (n_3 - n_2) \frac{c}{2(f_3 - f_2)} \\ \dots \\ d = \frac{c(\phi_N - \phi_{N-1})}{4\pi(f_N - f_{N-1})} + \frac{c(\Delta\phi_N - \Delta\phi_{N-1})}{4\pi(f_N - f_{N-1})} + (n_N - n_{N-1}) \frac{c}{2(f_N - f_{N-1})} \end{cases} \quad (10)$$

To represent the equation system more clearly, the following formula was constructed:

$$\begin{cases} \hat{r}_i = r_i + \Delta r_i \\ r_i = \frac{c(\phi_{i+1} - \phi_i)}{4\pi(f_{i+1} - f_i)} \\ \Delta r_i = \frac{c(\Delta\phi_{i+1} - \Delta\phi_i)}{4\pi(f_{i+1} - f_i)} \\ M_i = \frac{c}{2(f_{i+1} - f_i)} \\ \zeta_i = n_{i+1} - n_i \end{cases} \quad (11)$$

where the value of i ranges from 1, 2, ..., $N - 1$. Substituting the above formulas into equation group (11) yields the latest equation group:

$$\begin{cases} d = \hat{r}_1 + \zeta_1 M_1 \\ d = \hat{r}_2 + \zeta_2 M_2 \\ \dots \\ d = \hat{r}_{N-1} + \zeta_{N-1} M_{N-1} \end{cases} \quad (12)$$

From equation (12), a system of congruence equations based on multi-frequency carrier phase differences was established. By solving this system of congruence equations, the distance between the reader and the tag can be obtained.

3.4 Chinese remainder theorem with closed solution

From equation (12), we can see that a congruence relation related to distance and frequency has been established. By applying the Chinese Remainder Theorem to solve this congruence relation, distance information can be obtained. However, although the traditional Chinese Remainder Theorem is theoretically simple and computationally convenient, it is particularly sensitive to noise. Even minor random errors in actual measurement data can lead to significant inaccuracies in the results. Therefore, a Chinese Remainder Theorem with a closed-form solution is proposed to enhance the robustness of the system.

The Chinese Remainder Theorem with a closed-form solution allows for the inclusion of errors in the values of $\hat{r}_1$, meaning that $\Delta\phi_i$ ($i = 1, 2, \dots, N - 1$) can be non-zero. Based on the equations listed above, the following system of equations can be derived:

$$\begin{cases} d_0 = \zeta_1 \Gamma_1 + q_1 \\ d_0 = \zeta_2 \Gamma_2 + q_2 \\ \dots \\ d_0 = \zeta_{N-1} \Gamma_{N-1} + q_{N-1} \end{cases} \quad (13)$$

Using the first equation as a reference, the remaining equations can be sequentially subtracted from it, resulting in a system of equations in the following form:

$$\begin{cases} \zeta_1 \Gamma_1 - \zeta_2 \Gamma_2 = q_{2,1} \\ \zeta_1 \Gamma_1 - \zeta_3 \Gamma_3 = q_{3,1} \\ \dots \\ \zeta_1 \Gamma_1 - \zeta_{N-1} \Gamma_{N-1} = q_{N-1,1} \end{cases} \quad (14)$$

where $q_{i,1}$ represents the following meaning:

$$q_{i,1} = q_i - q_1 \quad (i = 1, 2, \dots, N - 1). \quad (15)$$

The value of $q_{i,1}$ can be calculated using the following formula:

$$q_{i,1} = \left[\frac{\hat{r}_i - \hat{r}_1}{M} \right], \quad i = 1, 2, \dots, N - 1. \quad (16)$$

The brackets $[\cdot]$ indicate rounding, and the expression for parameter $\zeta_{i,1}$ is as follows:

$$\zeta_{i,1} = q_{i,1} \hat{\Gamma}_{i,1} \bmod \Gamma_i, \quad i = 2, 3, \dots, N - 1, \quad (17)$$

where $\hat{\Gamma}_{i,1}$ $i = 2, 3, \dots, N - 1$ is the modular inverse of Γ_1 with respect to Γ_i , $i = 2, 3, \dots, N - 1$, and the parameters to be solved are represented as follows:

$$\begin{cases} \zeta_1 = \sum_{i=2}^{N-1} \zeta_{i,1} b_{i,1} \frac{\gamma_1}{\Gamma_i} \bmod \gamma_1 \\ \zeta_i = \frac{\zeta_1 \Gamma_1 - q_{i,1}}{\Gamma_i} \quad i = 2, 3, \dots, N - 1 \end{cases} \quad (18)$$

where $b_{i,1}$, $i = 2, 3, \dots, N - 1$ is the modular inverse of γ_1/Γ_i with respect to Γ_i .

3.5 Positioning method based on weighted LM

According to the ranging model based on phase difference and distance, the distances between multiple tags and the reader can be determined. Assuming the distance from the i -th tag to the reader is d_i , and the two-dimensional positions of the tags are known as (x_i, y_i) , while the coordinates of the reader's position to be located are (x, y) , if the reader can detect n tags, then the following system of non-linear equations can be established:

$$\begin{cases} \sqrt{(x - x_1)^2 + (y - y_1)^2} = d_1 \\ \sqrt{(x - x_2)^2 + (y - y_2)^2} = d_2 \\ \dots \\ \sqrt{(x - x_n)^2 + (y - y_n)^2} = d_n \end{cases} \quad (19)$$

Express the above equation as $f_i(p) = d_i$, and expand it at point p_k in Taylor series form, neglecting terms of second order and higher, to obtain $f_1(p) = f_1(p_k) + f_1'(p_k) \Delta p$. Then the least squares method can be used to solve for the value of Δp , that is, $\Delta p = (J^T J)^{-1} J^T \varepsilon$. After that, use p_{k+1} as the Taylor expansion point for the next iteration, gradually approaching the coordinates of the reader's position to be determined.



Figure 4. RFID hardware equipment. (a) RFID Reader. (b) Tag.

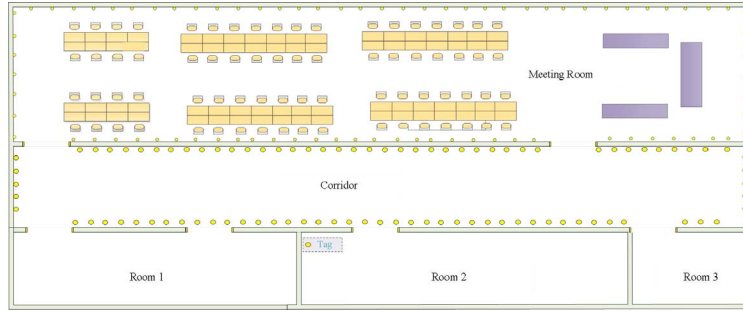


Figure 5. Floor plan of the experimental scenarios.

To ensure convergence speed and iteration stability, each equation in the positioning system that needs to be solved is assigned a weight, while the error data encountered during the positioning process is incorporated into the solution of the equation system. At this point, the nonlinear equations that need to be solved can be expressed in the following form:

$$\begin{cases} \sqrt{\omega_1}(J_{11}\Delta x + J_{12}\Delta y) = \sqrt{\omega_1}\varepsilon_1 \\ \sqrt{\omega_2}(J_{21}\Delta x + J_{22}\Delta y) = \sqrt{\omega_2}\varepsilon_2 \\ \dots \\ \sqrt{\omega_n}(J_{n1}\Delta x + J_{n2}\Delta y) = \sqrt{\omega_n}\varepsilon_n \end{cases} \quad (20)$$

The least squares solution of the weighted system of equations can be denoted as $\Delta p = (J^T W J)^{-1} J^T W e$. The fundamental principle of the LM method is to enhance the stability of the iterative process while ensuring the maximum allowable convergence speed. By utilizing the LM method to solve the initially obtained nonlinear ranging equations, we arrive at the parameter $\Delta p = (J^T J + \lambda I)^{-1} J^T \varepsilon$, where the parameter λ is constrained to be a positive real number, and I represents the identity matrix. On this basis, by further introducing a damping coefficient λ , the first-order convergent steepest descent method is combined with the second-order convergent Gauss-Newton method. Consequently, the calculation formula for parameter Δp changes to $\Delta p = (J^T W J + \lambda I)^{-1} J^T W e$.

4 Experimental results and analysis

4.1 Hardware systems

The hardware required for the indoor positioning experiment, as shown in Figure 4, mainly consists of two parts: an RFID reader and tags. The reader utilizes the Indy R2000 chip produced by Impinj, while the tags are passive, anti-metal tags that incorporate the Alien H3 chip. These tags support the ISO18000-6C EPC Gen2 air interface protocol and enable bidirectional communication with the reader antenna.

4.2 Experimental scenarios

We selected the two experimental scenarios due to the different floor areas and mobility that are depicted in Figure 5. The scenarios can be categorized into static and dynamic based on the mobility, which depends on the number of people present and the frequency of their mobility during experimentation. In the meeting room, it is almost static with three people sitting at their places most of the time during experimentation. In contrast, in the corridor, the people have frequent mobility, such as moving in and out of the place; therefore, it can be considered a typical dynamic environment.

The RFID tags were positioned at a height of 1.5 m above the floor, evenly spaced at intervals of 5 m in both horizontal directions. During the experiment, the reader

antenna was also maintained at a height of 1.5 m. To account for variations in signal strength and improve accuracy, each tag's signals were measured 100 times, allowing for averaging to reduce random effects. The collected data were then processed using the algorithm outlined in Section 3. This additional information enhances the understanding of the robustness and applicability of the algorithm under realistic conditions. The reader and tags communicate bidirectionally, identifying and reading the frequency and phase information of a reference tag. This information is then used in a ranging and positioning model to determine the location of the reader. Before the experiment, phase calibration is conducted to eliminate system errors. Specifically, the tags are placed in close proximity to the reader antenna, with the distance between the tag and the reader being zero. The phase value read at this moment is recorded, and this phase value, along with the corresponding frequency values, is documented for each frequency point under each tag. After obtaining and saving the calibration data for the reference tag, this value must be subtracted from the actual measured phase data.

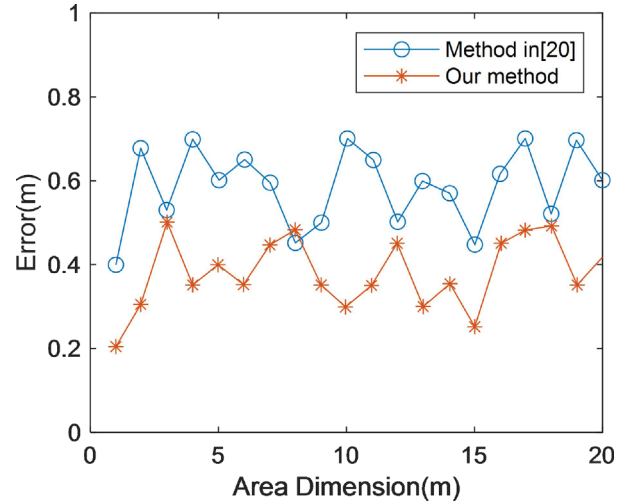
After obtaining the phase, frequency, EPC, and other information from the tags using the reader, we utilize the Gauss-Kalman model to filter the received phase data, thereby reducing the impact of environmental noise. Subsequently, we substitute the phase and frequency into the Chinese Remainder Theorem, which has a closed-form solution, to calculate the distances between the reader and multiple tags. Once we have determined the distances from multiple tags to the reader, we utilize the weighted LM positioning method along with the known coordinates of the tags to compute the position coordinates of the mobile reader.

4.3 Experimental results and analysis

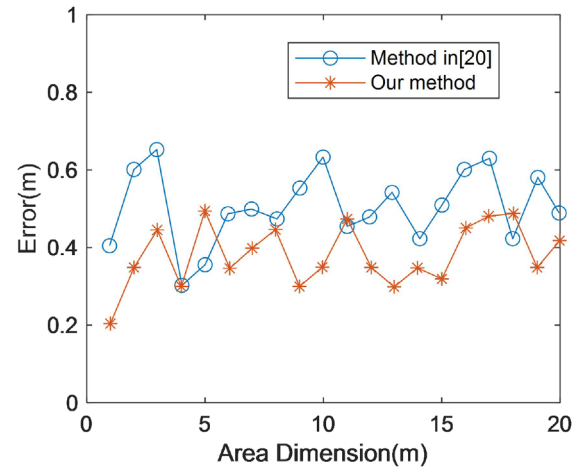
The evaluation metrics used in this study include the average positioning error and the Cumulative Distribution Function (CDF) of Localization Error. The average positioning error is defined as the mean of the absolute differences between the estimated positions provided by our algorithm and the actual locations of the RFID tags, serving as a direct measure of the algorithm's accuracy. In addition, the CDF represents the probability that the localization error is less than or equal to a certain value, offering a comprehensive overview of the distribution of localization accuracy. Together, these metrics provide a thorough assessment of the performance of our positioning algorithm.

During the experimental process, three frequencies of 902 MHz, 910 MHz, and 922 MHz were selected for distance estimation. To better validate the system's performance, this study compared its methods with those in reference [10] in the meeting room and corridor, respectively.

As shown in Figures 6a and 6b, the method proposed in this study achieves an average positioning error of 0.38 m and a maximum positioning error of 0.5 m in the meeting room. In contrast, the method presented in Reference [10] has an average positioning error of 0.58 m and a maximum error of 0.7 m, which is inferior to the method proposed in this study. In the corridor, the continuous movement of personnel significantly affects the signal due to multipath



(a) Localization error in meeting room



(b) Localization error in the corridor

Figure 6. Localization error in different scenarios. (a) Localization error in meeting room. (b) Localization error in the corridor.

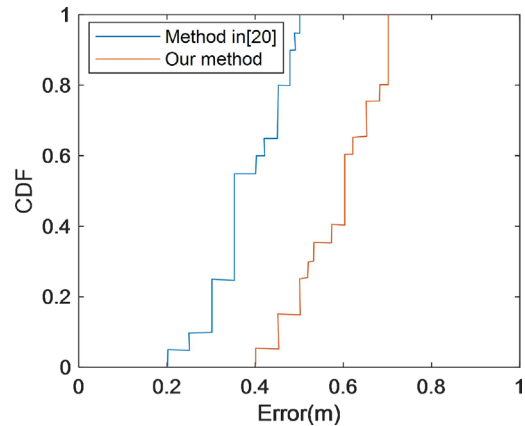


Figure 7. CDF of comparison of the Localization error.

interference, resulting in an increased positioning error, with an average error of 0.5 m and a maximum error of 0.65 m. Figure 7 illustrates the CDF of the comparison of the Localization error for the two positioning methods. It can be observed that the method from Reference [10] has an 80% probability of an error within 0.7 m, while the positioning method developed in this study has an 80% probability of an error less than 0.45 m, with all errors remaining within 0.5 meters, indicating more precise positioning results.

5 Conclusion

This study primarily utilizes the multi-frequency characteristics of high-frequency tags to achieve precise indoor positioning. Based on the analysis of carrier phase error suppression, a ranging method based on multi-frequency carrier phase differences is proposed. This method utilizes a closed-form solution to solve for phases with the Chinese Remainder Theorem and a Weighted Levenberg-Marquardt algorithm to compute the final tag's location. Through extensive experiments, the method reaches an average positioning error of 0.38 m, meeting the requirements for high-precision indoor localization. The next step could be adding additional 3D reference tags to enable 3D target positioning.

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Conflicts of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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