METROLOGY AT THE HEART OF
TODAY’S TECHNOLOGIES

Localization of Metallic Lost Tools Using UHF RFID System

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Abstract/Résumé

This paper presents an enhanced approach for localizing metallic objects in complex industrial environments using UHF RFID technology. We present an improved algorithm based on the Three-Ray Ground Reflection Model that addresses the limitations of traditional RSSI-based methods. Our solution demonstrates significant improvements in accuracy and reliability compared to conventional approaches, particularly in environments with multiple interference sources and reflection paths.

Cet article présente une approche améliorée de la localisation d’objet métalliques dans des environnements industriels complexes basée sur la technologie RFID UHF. Nous présentons un algorithme amélioré basé sur le modèle de réflexion a rois rayons qui compense les limotations des méthodes traditionnelles basées sur le RSSI. Notre solution offre une précision et une fiabilité accrues par rapport aux approches conventionnelles, en particulier, dans les environnements avec source multiple d’interférences et chemins de réflexions.

1 Introduction

Lost or misplaced metallic objects can lead to extended downtimes, significant financial losses, and operational disruptions. Therefore, accurate and reliable localization methods have become a critical area of research and development.While UHF RFID technology has been widely explored as a promising solution for object tracking due to its low cost, scalability, and non-line-of-sight capabilities, traditional methods often suffer from significant limitations. Specifically, they are vulnerable to signal interference, multipath effects, and reflections from metallic surfaces, all of which contribute to reduced localization accuracy and system reliability. Several previous studies have addressed these challenges through different approaches. IoT-based smart warehouse systems have been proposed, integrating RFID with wireless sensor networks to enhance localization and environmental monitoring [1]. Deyle et al. [2] optimized the received signal strength for object detection in domestic environments using directional antennas and sparse sampling strategies, while DiGiampaolo and Martinelli [3] developed a two-stage probabilistic framework based on phase measurements for tracking RFID-tagged objects on warehouse shelves. Despite these , existing methods still face serious challenges when deployed in complex industrial environments with numerous metallic surfaces.Our research aims to improve localization accuracy in advanced industrial facilities. In particular, we propose an enhanced localization algorithm based on the Three-Ray Ground Reflection Model, which more accurately captures the key signal propagation phenomena : direct transmission, ground reflection, and object reflection that dominate in metallic environments. By leveraging phase measurements instead of relying on RSSI, and by integrating the complex multipath behavior into the model, our approach significantly enhances localization precision and robustness.

The rest of this paper is organized as follows: Section 2 describes the proposed localization algorithms and details the Three-Ray Ground Reflection Model. Section 3 presents the implementation flow, simulation setup, and key experimental results. Section 4 concludes the paper with a summary of contributions and future perspectives for industrial deployment.

2 State of Art

The problem of RFID-based localization, particularly in environments with metallic interference, has been actively studied in recent years. Early methods based solely on RSSI measurements were shown to be highly sensitive to multipath effects and environmental noise, leading to limited accuracy in industrial contexts. To address these challenges, models based on phase information and electromagnetic propagation characteristics have been proposed. The work by DiGiampaolo and Martinelli [3] introduced a mobile robot localization technique based on the phase of passive UHF RFID tags. Their system collects phase measurements along a planned trajectory and matches them to an electromagnetic model to estimate the tag position. Specifically, they proposed a two-stage localization strategy:

- First, the robot moves along a path parallel to a shelf to estimate the horizontal coordinate of the tag, exploiting the symmetry of the phase pattern.
- Second, a movement perpendicular to the shelf allows estimation of the vertical coordinate, refining the tag position.
The phase model used in their approach relates the measured phase ϕ_i at a robot position si=(x_i,y_i,z_R) to the tag position (x_T,z_T) through equation 1.

$$\phi_i = \mathrm{mod}\left(-2K\sqrt{(x_i - x_T)^2 + y_i^2 + (z_R - z_T)^2} + \phi_d + \theta_n, \pi\right) \quad (1)$$

Where :

$K=\frac{2\pi}{\lambda}$ *: The wavenumber,*
ϕ_d *: Represents a constant phase offset,*
θ_n *: The measurement noise,*
and the modulus operation accounts for phase wrapping due to limited unambiguous range.

This model exploits the fact that phase variations exhibit a local maximum when the robot passes directly in front of the tag, corresponding to the point of minimal distance. While this approach proves highly effective in semi-structured environments like warehouses, it relies on relatively simple propagation assumptions and primarily considers direct-path transmission. In contrast, real-world industrial environments often involve significant signal degradation caused by ground reflections, object-induced multipath effects, and metallic clutter. These conditions severely impact phase consistency and localization precision.

In parallel with this theoretical analysis, we developed and tested an initial localization method, referred to as Algorithm A. This approach uses a grid-based Breadth-First Search (BFS) strategy combined with Received Signal Strength Indicator (RSSI) measurements. The user or robot starts at a known entry point (typically at coordinates (0,0)) and explores adjacent positions in the grid. At each step, RSSI values are measured and compared across directions (e.g., positions (1,0) and (0,1)). The system then moves toward the direction with the stronger RSSI signal, gradually converging toward the tag location. The logical flow of this method is illustrated in Figure 1.

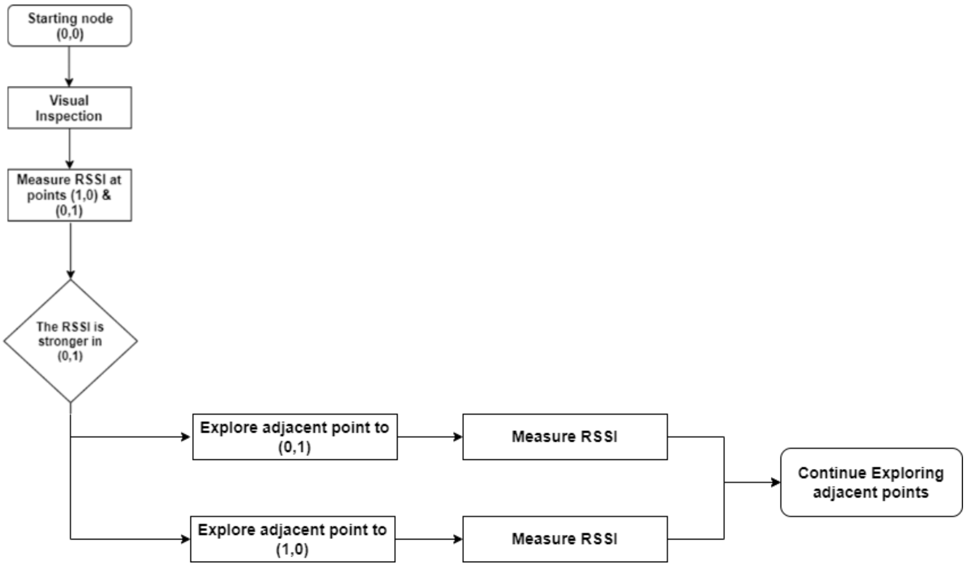

Figure 1: Algorithm A : Step by Step Execution Flow

Although Algorithm A offers a simple and low-cost solution, it suffers from severe limitations in metallic environments. Strong reflections and multipath interference often cause unpredictable fluctuations in RSSI, which can mislead the system and lead to false convergence. Building on this foundation, our work introduces an enhanced phase-based localization approach, incorporating a more advanced signal propagation model :The

Three-Ray Ground Reflection Model. This approach represents the main multipath components encountered in metallic industrial settings and enables accurate tag localization even under complex environmental conditions.

3 Proposed Method: The Three Ray Ground Reflection Model

To overcome the limitations observed with traditional RSSI-based methods and basic grid exploration strategies (Algorithm A), we developed a new localization approach tailored for metallic environments, referred to as Algorithm B. This method leverages a refined electromagnetic propagation model based on the Three-Ray Ground Reflection Model to improve localization accuracy and robustness.

Unlike traditional models that consider only the direct path between the reader and the RFID tag, the Three-Ray Ground Reflection Model incorporates three distinct signal components that influence the received signal:

- Direct Path (d_1): The straight-line signal traveling directly from the transmitter T_x to the tag R_x.
- Ground-Reflected Path (d_2): The signal that reflects off the ground surface before reaching the tag.
- Object-Reflected Path (d_3): The signal that reflects off the surface of the metallic object itself before being received.

These three propagation paths contribute to the final signal phase and amplitude detected at the reader. The model illustrated in Figure 2 provides a more accurate and realistic representation of signal behavior in environments where metallic surfaces introduce significant multipath interference. In this context, x_r represents the horizontal distance between the transmitter and the receiver. This distance directly affects the calculation of the path lengths d_1, d_2, and d_3, which in turn influence both the signal phase and strength at the receiver.

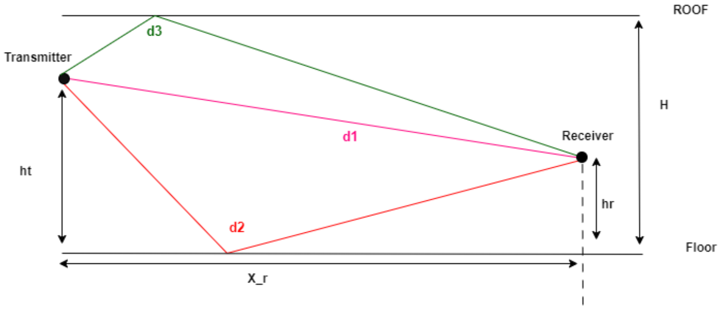

Figure 2:: Visualization of the Three-Ray Ground Reflection Model

By considering these three contributions, the model better captures the complex multipath behavior typical of industrial environments, where reflections and interference are prevalent. Each path introduces different phase shifts and signal strengths, and their combination affects the measured phase at the reader.

To analyse the effect of these paths on the signal phase, it is necessary to quantify the phase shifts introduced by each path relative to the direct path. In the context of multipath propagation, it is critical to evaluate the phase difference introduced by each reflected signal path relative to the direct path. These differences directly influence the total measured phase at the receiver due to constructive or destructive interference. Specifically, the phase differences between the direct path and the reflected paths, equation 2 define the ground-reflected path and the object-reflected path :

$$\Delta\phi_g = \frac{2\pi}{\lambda}(d_2 - d_1) \; ; \; \Delta\phi_o = \frac{2\pi}{\lambda}(d_3 - d_1) \qquad (2)$$

Where d_1 is the length of the direct path, d_2 is the length of the ground-reflected path, and d_3 is the length of the object-reflected path visualize in figure 2. To model the phase behavior of the signals with high accuracy, we developed a new phase equation based on trigonometric identities, specifically the Law of Cosines (also known as Al-Kashi’s theorem). Equation 3 describes the geometric relationships between the RFID reader, the RFID tag, and the reflection points, allowing the determination of phase differences between different signal paths.

The key angles involved in this model such as the angles of incidence and reflection are critical for linking the heights of the transmitter and receiver with the horizontal distances separating them.To accurately describe the propagation paths, we applied fundamental trigonometric principles to these geometric relationships. By leveraging triangle similarity and applying the Law of Cosines, we established precise mathematical expressions that relate the horizontal distance, the heights of the reader and tag, and the signal propagation angles. These relationships allow us to calculate exact path lengths, which are essential for determining the phase differences between the direct and reflected signals.In the subsequent calculations, we derive the phase difference by define in equation 3 directly using these geometric formulas.

$$\Delta\phi = \frac{2\pi}{\lambda}\left(\frac{((H-h_t)+(H-h_r))\sqrt{d^2-4(H-h_t)(H-h_r)}}{\sqrt{((H-h_t)^2+(H-h_r)^2\ -2(H-h_t)(H-h_r))}} - \sqrt{(h_r-h_t)^2+d^2}\right. \qquad (3)$$

This detailed modeling enables more accurate estimation of phase differences caused by geometry and environmental features. It forms the core of the Three-Ray Ground Reflection Model and is fundamental to our phase-based localization strategy. Unlike simpler models, this approach adapts to realistic configurations and provides enhanced resolution in complex industrial environments.

To account for multiple signal paths, the total received signal rtot(t)) is defined in the equation 4 as the coherent sum of all individual signal components ri(t) arriving at the receiver from different propagation paths, including the direct path and reflected paths.

$$r_{\text{tot}}(t) = \sum_{i=1}^{N} r_i(t) \qquad (4)$$

Each $r_i(t)$ represents a signal that travels along a specific path of length d_i, with its own strength and phase shift.

The received power P_r is computed as the time-averaged squared magnitude of the total received signal, as defined in equation (5) for the Three-Ray model. This formulation offers a more precise characterization of signal behavior in complex industrial environments, where multipath effects and reflections significantly impact signal strength and phase.

$$P_r = \langle |r_{\text{tot}}(t)|^2 \ = P_r = P_{\text{los}}(1 + r_1^2 + r_2^2 + 2r_1\cos(\Delta\phi_1) + 2r_2\cos(\Delta\phi_2) + 2r_1r_2\cos(\Delta\phi_1 - \Delta\phi_2)) \qquad (5)$$

Where :

$P_{los} = \frac{G\lambda}{(4\pi d)^2}^2$

$r_1 = \frac{d}{x_{1} + x'_1}$ *: The ratio for the ground-reflected path,*

$r_2 = \frac{d}{x + x'}$ *: The ratio for the object-reflected path,*

$\Delta\phi_1$ *and* $\Delta\phi_2$ *: The phase differences between the direct path and each reflected path, respectively*

3.1 Simulation and Evaluation

To evaluate the proposed phase-based localization approach, we implemented Algorithm B based on the Three-Ray Ground Reflection Model. The algorithm operates by comparing measured phase values with theoretical phase patterns generated from the model, identifying the location that minimizes the phase error.

The logic of the algorithm is illustrated in Figure 3, which outlines the two-step estimation process: first along the x-axis (parallel movement) and then along the y-axis (orthogonal refinement). At each step, the reader collects phase data, which are then matched to predicted phase curves.

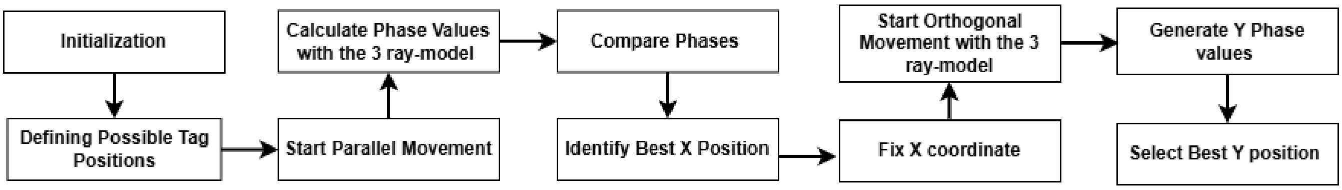

Figure 3 : Flowchart of the simulation based localization algorithm

For each tag position, the simulation computed predicted phase values using the multi-ray model and compared them to measured phases along discrete X-axis positions. The position with the lowest Mean Squared Error (MSE) was selected as the best estimate. As shown in Figure 4, the peak in measured phase indicates the estimated X-coordinate of the tag, allowing the algorithm to localize the tag accurately along the X-axis.

Once the X-coordinate was determined, the algorithm proceeded with a similar process along the Y-axis, using orthogonal movement to refine the tag's vertical position. The simulation estimated the tag's position with high accuracy, yielding an X-coordinate of approximately 4.49 (close to the actual 4.5) and a Y-coordinate of 0.0, matching the true location. Figure 5 illustrates this precision, showing the close alignment between estimated and actual positions along both axes. These results validate the effectiveness of the proposed multi-ray localization algorithm in accurately identifying tag positions, even in multipath environments.

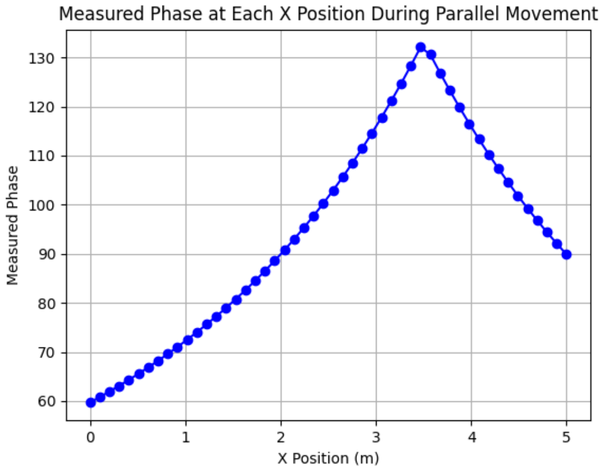

Figure 4 : Measured Phase at Each X Position During Parallel Movement

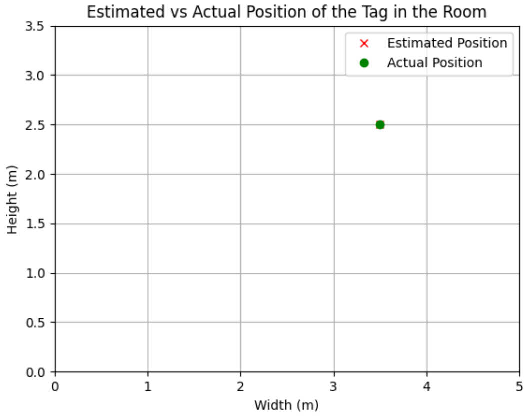

Figure 5 : Comparison of Estimated and Actual Tag Position with Phase Prediction Analysis

Furthermore , figure 6 compares measured and predicted phase values during both stages of the localization process: parallel (X-axis) and orthogonal (Y-axis) movements. In the parallel phase, the close alignment between the measured and predicted curves confirms the accuracy of the estimated X-coordinate . Similarly, in the orthogonal phase, the estimated Y-coordinate closely matches the predicted values, further validating the algorithm’s effectiveness in refining tag localization through two-axis phase analysis.

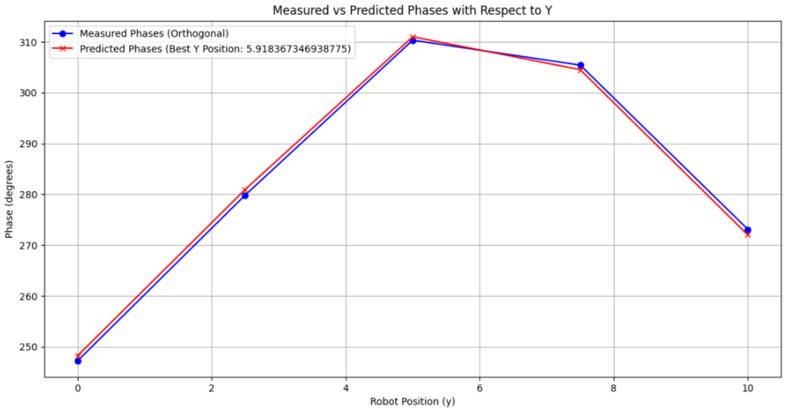

Figure 6 : Measured vs Predicted Phases During Orthogonal Movements for Localization

4 Conclusion

This work addressed the challenge of localizing metallic objects using UHF RFID in complex industrial environments. Two algorithms were developed and evaluated: Algorithm A, based on RSSI and grid movement, performed adequately in simple settings but struggled with multipath interference. To overcome these limitations, Algorithm B was introduced, using a Three-Ray Ground Reflection Model and later extended to a Five-Ray and generalized N-Ray model. This advanced approach incorporates phase calculations and multiple reflection paths, offering significantly improved accuracy in metallic environments. The results confirm the potential of multi-ray RFID models for reliable object localization and highlight promising directions for future research and industrial application.

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