RF-Monitor: Smart RFID Solution for Industrial Electrical Cabinet Door Monitoring

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Abstract

In industrial settings, detecting electrical cabinet door states is essential for safety and security. This paper introduces a novel RFID-based system that utilizes the multipath environment within electrical cabinets. Changes in RSSI and phase data occur when the door opens or closes, allowing accurate detection of door state transitions. By employing a multi-tag strategy and robust feature construction, our system ensures reliable signal reception and precise detection, even in challenging environments. Extensive long-term experiments demonstrate its accuracy and effectiveness, proving its suitability for practical applications.

CCS Concepts

• **Computer systems organization** → *Embedded systems*; • **Information systems** → *Data streaming*.

Keywords

RFID, Multipath environment, RSSI, phase, Industrial electrical cabinet, Door state detection

ACM Reference Format:
Haocheng Jiang, Fei Shang, Yubo Yan, Haohua Du, Xianrui Pan, and Xiangyang Li. 2024. RF-Monitor: Smart RFID Solution for Industrial Electrical Cabinet Door Monitoring. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation emai (RF-Com'24).* ACM, New York, NY, USA, 5 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Monitoring the state of electrical cabinets in industrial scenarios is crucial for ensuring both safety and operational integrity.[4, 7, 18] Within this context, two critical aspects are temperature monitoring inside the cabinets and detecting the state of cabinet doors. Due to the passive nature of RFID tags, using RFID temperature-sensing tags to monitor the temperature inside electrical cabinets is already a common practice in the industry; these tags are placed within the cabinets to offer continuous temperature data.[10, 17]

Traditional methods for monitoring the state of cabinet doors typically involve active sensors that require a constant power supply and are prone to mechanical wear and tear.[1, 5, 9] These issues motivate the need for a more reliable, cost-effective solution. Building upon the existing RFID temperature monitoring setup, we propose extending the functionality of these RFID systems to also monitor cabinet door states, eliminating the need for additional costly hardware.[2]

Unlike wooden cabinets, which tend to absorb signals,[3] metal electrical cabinets exhibit strong reflective properties, resulting in a pronounced multipath environment.[12] This characteristic complicates the task of determining the door state using a single RFID tag placed on the door. Given the impracticality of eliminating this multipath environment, we leverage it to our advantage for detecting the cabinet door status.

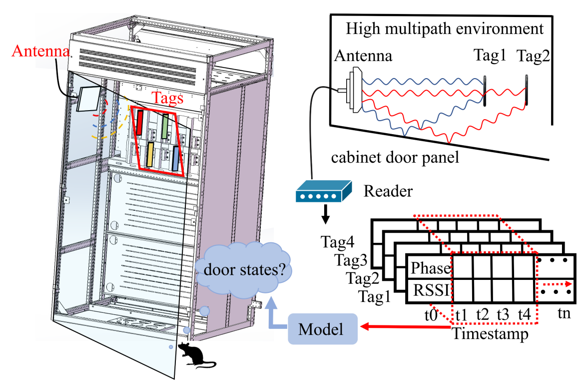

Figure 1: Industrial Electrical Cabinet Door State Detection

When the cabinet door is opened or closed, it alters the multipath signal reflections within the cabinet, leading to discernible variations in both the Received Signal Strength Indicator (RSSI) and phase information. In our proposed solution, we exploit this multipath effect induced by the movements of the cabinet door. By strategically deploying multiple RFID tags within the cabinet, we

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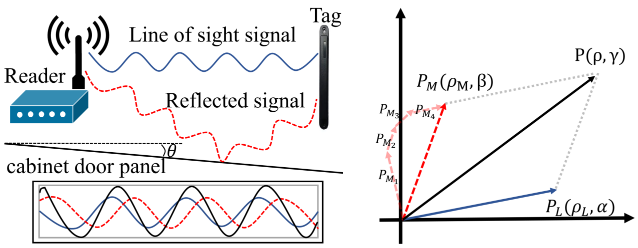
RF-Com'24, November 04–07, 2024, Hangzhou, China

ACM ISBN 978-1-4503-XXXX-X/18/06
https://doi.org/XXXXXXX.XXXXXXX



(a) LOS and reflected signal (b) wave superposition

Figure 2: Signal Propagation Model of RFID in Cabinet

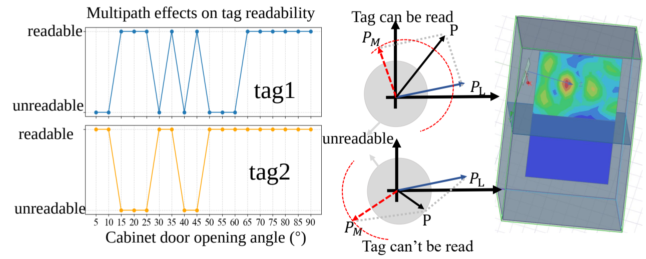


Figure 3: Multipath interference results in the tag not being read

can capture the resultant changes in RSSI and phase information caused by the door's varying positions. These variations serve as reliable indicators of the door state. By systematically analyzing the combined data from multiple tags, we construct robust multi-dimensional features that accurately reflect whether the cabinet door is open or closed. As show in Figure1. This method extends the functionality of existing RFID-based temperature monitoring systems to include reliable cabinet door state detection, thereby achieving dual functionality without incurring additional costs.

Our experiments demonstrated that relying on RSSI alone is insufficient for accurately detecting cabinet door states due to its weak correlation with door positions. Therefore, we constructed a set of stable, multi-dimensional features using RSSI and phase data from multiple RFID tags. This multidimensional approach allowed for more accurate determination of door states, transforming the RFID-based temperature monitoring system into a dual-purpose tool that also reliably detects cabinet door status without any additional cost.

2 RFID Multipath Analysis within Electrical Cabinets

RFID is a wireless technology that identifies and tracks objects using electromagnetic fields. It consists of three main components: RFID tags, reader, and antenna. RFID tags, which have a microchip and an antenna, can be active (battery-powered) or passive (powered by the reader's signal). RFID readers emit radio waves to communicate with tags, read their data, and process it, and can be either fixed or handheld. The antenna enables communication by transmitting the reader's radio waves and receiving the tag's response.[6, 8, 11]

To accurately detect the state of electrical cabinet doors in industrial settings using RFID technology, it is crucial to first comprehend the signal propagation model of passive RFID systems. In such systems, passive RFID tags communicate with RFID readers by backscattering electromagnetic signals. The propagation and reflection of signals within an electrical cabinet can be simplified as shown in Figure2. The environment within industrial cabinets often includes numerous reflectors, resulting in the received signal at the reader being a combination of the line-of-sight (LOS) signal P_L and multiple multipath signals P_{M_m}. [14, 15]

$$P_M = P_{M_1} + P_{M_2} + \ldots + P_{M_m} \quad (1)$$

These signals superimpose at the reader's antenna, forming a combined received signal $P(\rho, \beta)$, which can be mathematically expressed as:

$$P(\rho, \gamma) = \rho_L \cdot \cos(2\pi f \cdot t_L + \alpha) + \rho_M \cdot \cos(2\pi f \cdot t_M + \beta) \quad (2)$$

Where: f is signal frequency, identical for both LOS and multipath signals. t_L and t_M are transmission times of LOS and multipath signals, respectively. γ, α, β are phases of the received signal, LOS signal, and multipath signals, respectively. ρ, ρ_L, ρ_M are amplitudes of the received signal, LOS signal, and multipath signals, respectively.

The amplitude ρ can be estimated using the Received Signal Strength Indicator (RSSI).$\rho = 10^{\frac{RSSI}{1000}}$.Due to the strong reflective properties of the metal electrical cabinet doors, the amplitude of the multipath signal ρ_M will be roughly similar to that of the LOS signal ρ_L.[13, 16]

In our proposed method for detecting the door states of electrical cabinets, we utilize the variations in RSSI and phase information caused by the door's movement. When the cabinet door opens or closes, the reflections of the signals within the cabinet change, altering the multipath signal components. By strategically deploying multiple RFID tags within the cabinet, we can capture these changes in RSSI and phase data.

Due to the multipath superposition, when the electrical cabinet door opens at different angles, the reflection paths change, leading to scenarios where the multipath signals and the LOS signal destructively interfere. This can result in certain RFID tags becoming unreadable at specific door opening angles. As shown in Figure3, coupled with the effects of multipath propagation, the signal strength varies at different locations within the electrical cabinet. Furthermore, when the LOS (Line of Sight) path signal and the multipath signals at a certain location cancel each other out, causing the received power of the tag to be below its sensitivity threshold, the tag cannot be read. To validate this, we conducted experiments to observe this phenomenon. By strategically placing multiple RFID tags within an electrical cabinet and recording their readability as the door was opened at various angles, we found that certain tags became unreadable when the cabinet door was opened at specific angles, confirming the presence of destructive interference between the multipath and LOS signals.

Our findings underscore the necessity of deploying multiple RFID tags and strategically positioning them to ensure reliable detection of the cabinet door state across various conditions.

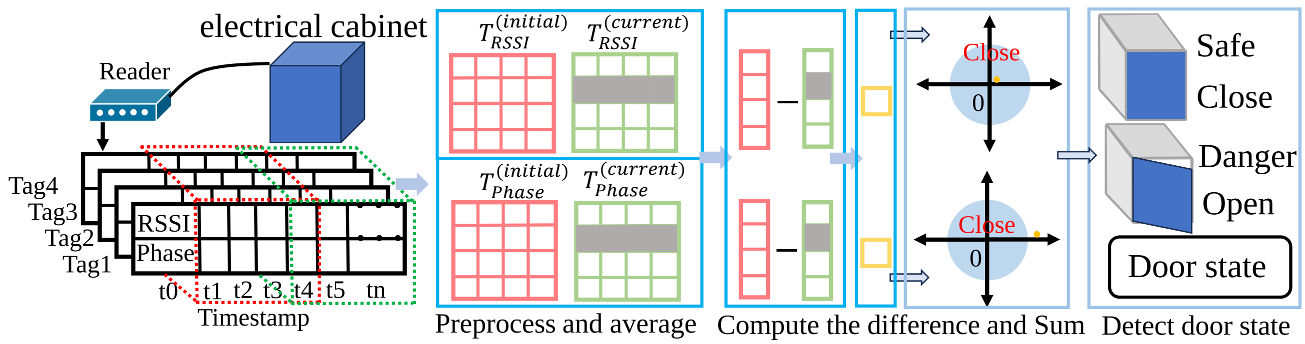


Figure 4: Framework for Detecting Cabinet Door State.The reader continuously reads tag data, starting with the initial state when the cabinet door is closed. The data is preprocessed to calculate the differences between the initial and current tag data. The summed differences in RSSI and phase values for all tags are compared against a threshold to determine the cabinet door state.

3 System Design

3.1 Tag Deployment Strategy

To address the issue of destructive interference and resultant unreadability of RFID tags at certain door opening angles, we propose a novel tag deployment strategy. Specifically, we arrange multiply RFID tags such that the adjacent tags are approximately one-quarter wavelength ($\lambda/4$) apart. This configuration ensures that the tags do not simultaneously experience a null point (i.e., a wave trough) due to multipath effects, thereby mitigating the risk of simultaneous unreadability. The tags are positioned such that no more than one tag is likely to be in a null point at any given time. This strategic placement is critical for maintaining reliable detection of the cabinet door state across varying conditions.

3.2 Initial State Determination

In industrial settings, especially for medium- and high-voltage electrical cabinets, it is imperative to ensure the safety of personnel by closing the cabinet door before applying power. Therefore, the initial condition of the system assumes the cabinet door is closed. Under this assumption, the reader collects baseline RSSI and phase information from each of the multiply tags.

To minimize random errors and enhance reliability, each tag is read multiple times to form a data set. All individual readings are then used for subsequent analysis. The first set of readings serves as a reference point for the closed-door state. Subsequent sets of readings are compared against this baseline to detect changes indicative of door movement.

3.3 Door State Detection Algorithm

The framework for detecting cabinet door state is shown in Figure4. Let $\mathbf{T}_{\text{RSSI}}^{(\text{initial})}$ and $\mathbf{T}_{\text{RSSI}}^{(\text{current})}$ denote the matrices representing the *RSSI* values for the initial and current readings, respectively. Similarly, let $\mathbf{T}_{\text{phase}}^{(\text{initial})}$ and $\mathbf{T}_{\text{phase}}^{(\text{current})}$ denote the matrices representing the phase values for the initial and current readings, respectively. The matrices are structured such that each row represents a single tag, and each column represents one of the four readings.

To enhance algorithm robustness, outlier values in the *RSSI* and phase data are filtered over a predefined period. Then, average *RSSI* and phase values for each tag are calculated. The differences between these averages and the initial closed-door state values are computed, and their absolute values represent the changes in *RSSI* or phase for each tag, indicating the deviation from the initial state.

If a tag was readable in the initial closed-door state but becomes unreadable in a subsequent state, a specific predefined value is assigned to both the *RSSI* and phase change values for that tag. This predefined value needs to be carefully chosen to accurately reflect the significant change associated with a tag becoming unreadable without overly skewing the results.

After calculating the RSSI and phase change values for each tag, these values are summed to obtain the total RSSI and phase change values for the system. This summation helps evaluate the overall signal changes due to the door's movement. The total RSSI and phase change values are then analyzed to determine the cabinet door state. When the door is closed, these values remain relatively small, reflecting minor variations from environmental noise or slight positional shifts. However, if the summed values exceed a pre-determined threshold, it indicates significant changes in RSSI and phase values, suggesting that the cabinet door has been opened. Establishing this threshold is crucial and must be based on empirical data to ensure a balance between sensitivity and reliability.

To ensure accurate and reliable detection, the algorithm continuously updates and checks change values against the threshold. By aggregating individual tag readings and eliminating random fluctuations and noise, this refined approach robustly monitors the cabinet door state. It accounts for the variability and inconsistencies in *RSSI* and phase information, leading to a dependable detection system that can trigger alerts or actions based on the door's state.

4 Experiments

To validate our proposed method for detecting the door states of electrical cabinets using RFID technology, we conducted a series of controlled experiments. These experiments were designed to capture variations in RSSI and phase information caused by the door's movement. Specifically, we analyzed the distributions of the

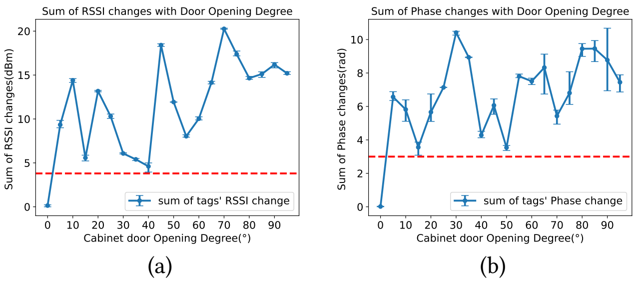


Figure 5: The sum of the changes in the RF parameters of all tags with the angle of the electrical cabinet door opening. (a) Sum of RSSI changes with door opening degree, (b) Sum of phase changes with door opening degree.

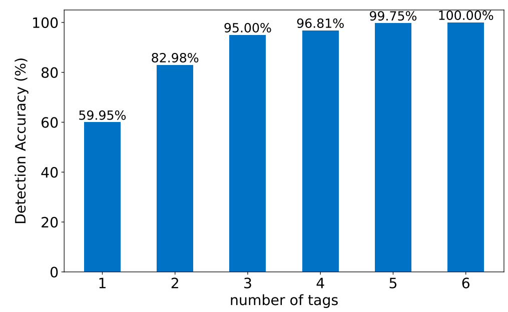


Figure 7: The impact of the number of used tags on the accuracy of door state detection.

sum of RSSI and phase changes of all tags at different angles and also examined the impact of the number of tags on the accuracy of determining the cabinet door state. These analyses enabled us to set appropriate thresholds and determine the optimal number of tags for accurately detecting whether the cabinet door is open or closed.

4.1 Experimental Setup

The experimental setup consisted of an electrical cabinet with dimensions 1.1m × 1m × 1.8m, a RFID reader and multiple passive UHF RFID tags (915MHz), as shown in Figure6. The distance between adjacent tags was approximately a quarter of the wavelength of the operating frequency. The RFID reader was positioned to consistently communicate with the tags and record the necessary RSSI and phase data.

Figure 6: Experimental setup. Include Electrical Cabinet, Reader, Tags, Antenna

4.2 Data Collection

To capture the necessary data, we conducted experiments with different numbers of tags. For each set of tags, the cabinet door was opened at various angles, starting from 0° and increasing in 5° increments. At each angle, multiple samples of RSSI and phase data were collected. Initial readings were taken with the cabinet door fully closed to establish baseline RSSI and phase values for comparison. This approach allowed us to rigorously assess the impact of door movement on RFID signal characteristics and validate our method for detecting changes in the door state based on these signal variations. By systematically varying the number of tags and recording multiple sets of data at each door angle, we ensured that our analysis would be robust and able to account for different tag configurations.

4.3 Results

The results of the experiments are summarized in Figure5 and Figure7 . Figure5 illustrate the sum of the changes in RSSI and phase values of four tags with respect to the degree of the cabinet door opening, Figure7 shows the impact of the number of tags on the accuracy of door state detection.

RSSI and Phase Changes: Figure 5(a) demonstrates that the sum of the changes in RSSI values of all tags is significantly higher when the cabinet door is open compared to when it is closed. When the cabinet door is closed, the sum of the RSSI changes is almost zero. Similarly, Figure 5(b) shows that the sum of the phase changes of all tags behaves the same way: it is substantially greater when the door is open and almost zero when the door is closed. Therefore, these measurements can be used to determine whether the cabinet door is open or closed.

Impact of Number of Tags on Detection Accuracy: Figure7 demonstrates the impact of the number of tags on the accuracy of door state detection. The detection accuracy improves significantly with an increasing number of tags. With just one tag, the accuracy is approximately 59.95%. However, this accuracy increases sharply to 82.98% with two tags and further to 95.00% with three tags. The detection accuracy continues to rise, reaching near perfection with five and six tags, achieving 99.75% and 100.00% accuracy, respectively.

5 Conclusion

In this paper, we introduced a novel RFID-based system for reliably detecting the state of electrical cabinet doors in industrial environments. By leveraging the multipath environment and strategically deploying multiple tags, our method effectively utilizes variations in RSSI and phase data to determine door states accurately. Extensive experiments demonstrated the system's robustness and high accuracy, thereby ensuring both safety and operational efficiency in industrial settings.

6 Acknowledgments

The research is partially supported by NSFC with No. 62072424, U20A20181, Key Research Program of Frontier Sciences, CAS. No. ZDBS-LY-JSC001, Hefei Municipal Natural Science Foundation with No. 2022016, the Fundamental Research Funds for the Central Universities with No. WK3500000008.

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Received 20 February 2024; revised 12 March 2024; accepted 5 June 2024