BOHR International Journal of Operations Management Research and Practices
2025, Vol. 4, No. 1, pp. 1–11
DOI: 10.54646/bijomrp.2025.32
www.bohrpub.com

RESEARCH STUDY

Operational excellence through passive RFID: Rapid deployment solutions for indoor localization

Mike C. Chang[1*], Stanford Martinez[1], Adel Alaeddini[2] and Hung-da Wan[1]

[1]Department of Mechanical Engineering, The University of Texas at San Antonio, San Antonio, TX, USA
[2]Department of Mechanical Engineering, Southern Methodist University, Dallas, TX, USA

[*]**Correspondence:**
Mike C. Chang,
chi-wen.chang@utsa.edu

[†]**ORCID:**
Mike C. Chang
0000-0003-0070-9119

Received: 26 September 2024; **Accepted:** 06 January 2025; **Published:** 22 January 2025

The demand for indoor positioning has grown significantly due to applications that rely on location awareness in spaces such as medical facilities, warehouses, and smart buildings. Unlike outdoor environments, where global positioning system operates effectively, indoor positioning faces the challenges of signal blocking and multipath effects common in enclosed areas. Current solutions such as Wi-Fi, Bluetooth, and Ultra-Wideband (UWB) provide effective results, but they often involve high costs and complex install processes, especially in big settings. Given these challenges, passive radio frequency identification (RFID) has become a viable choice for indoor positioning. Not only the technology is cost-effective, but also eliminates the need of active power supply to its tags, making efficiency increase. This paper is proposing a passive RFID-based positioning system which designed for rapid deployment to solve signal interference, a common problem in the area with neighboring small spaces. We explore the limitations of the current RFID system and propose simple strategies to ensure location accuracy with minimal installation needs.

Keywords: rapid deployment, passive UHF RFID, anti-jamming algorithm, indoor localization, RFID software

Introduction

RFID technology has been widely utilized because of its advanced capabilities beyond traditional barcodes, especially through more advanced information encoding (1) and wireless communication (2). These attributes broaden its application in identification systems (ID) (3), covering areas such as long-range automatic dependent surveillance-broadcast (ADS-B) (4), near-field communication (NFC) (5), and various media types (6). Over time, RFID technology expands its use from basic identification to more complex applications, such as indoor localization (7).

One common method in indoor localization is identifying room occupancy. For example, in Kim et al. (8), the estimation of occupancy using CO_2 levels detected by IoT sensors offers positioning accuracy effective in specific zones (9). In addition, localization technology is widely used in industries like construction (10, 11), healthcare (12, 13), robotics (14), logistics (15), and automotive tracking (16). Radio frequency (RF) technology improves the sensing ability, making it possible for detecting signals across different devices.

The Received Signal Strength Indicator (RSSI) in RF technology is widely used in many fields, especially for measuring the distance. However, a key challenge of using RFID in accurate distance estimation is the RSSI value's uncertainty. This uncertainty becomes more complicated by the interaction of RF waves between RFID tags and the influence from multipath effect (17). When many RFID tags are in the range of RFID reader, the interaction of RF waves can cause interference and make fluctuations in

RSSI measurement. Furthermore, the multipath effect, where signal bounces off surface and create additional pathway, is challenge for accuracy of distance measurements.

Instead, exact indoor positioning, this research focuses on the issue of RF interference by creating an RFID-based localization system for detect object presence at room level, which enables efficient tracking in public areas. In this setup, precise position is not the main purpose; the goal is to identify if the RFID tag is in a certain room. To solve this problem, an algorithm is designed to evaluate individual RFID RSSI readings from each reader in different rooms, which helps detecting if single object is present. Location detection is simplified by comparing the primary location with the positions of the RFID readers. Furthermore, a cloud-based platform has been developed to access the localization system, offering enhanced data on tracked objects and enabling clearer visualization of their movement.

The research challenge focuses on 2 key aspects:

1. Reducing RFID interference issues in environments with dense signal populations.
2. Ensuring rapid deployment of the system.

The structure of this paper is as follows: Section 2 covers the background on indoor localization and passive RFID technology. Section 3 explains the proposed methodology and the experiment conducted to achieve rapid deployment, along with the software design. Section 4 presents the visualization results from the experiments. Lastly, Section 5 concludes the findings.

Background

The ultra-high frequency (UHF) band was selected as the most suitable RFID type, especially in cases where energy transfer is crucial for passive RFID distancing. Out of the multiple choices, the option of the ISO-18000-6C standard has been preferred, given its widespread recognition (18). In contrast to the more frequently used LF (low frequency) 125 kHz RFID systems, typically used for close-range ID scanning with a limited reach of less than 30 cm, the UHF option chosen here operates in the 860–960 MHz range, making it more suitable for mid-range areas.

For tracking items dispersed across multiple floors, the UHF passive RFID system is ideal, offering a scannable range of over 1 m and extending up to 15.5 m (19). This method offers a valuable contribution by presenting an affordable and scalable solution, applicable to various fields such as asset tracking and environmental monitoring. It ensures efficient performance while catering to a broad spectrum of use (3, 20).

Range-based method

The range-based method in this study works on the principle that signal strength decreases as the distance between the RFID reader and tag are increasing, which making the RSSI values a good proxy for estimating the distance (21–23). Accurate distance measurement is very important to effective localization of monitoring objects, with RF providing the basic physical property for this purpose. The speed of electromagnetic waves is giving a reliable way for estimate the distance between the transmitter and receiver. Many systems, like radar and sonar, use metrics like Time of Arrival (ToA) and Time Difference of Arrival (TDOA) to decide this spatial relationship (24), which are common in global positioning systems and light detection and ranging technology (25). ToA finds the distance by measuring the travel time of a signal between transmitter and receiver, then multiplies this time (T) by the speed of light (C) to get the total distance. This calculation can also be represented as:

$$R = \frac{T \times C}{2} \tag{1}$$

representing the range (R) of radar detection.

Alternatively, the decay of an electromagnetic signal can be used to determine distance, as outlined by several parameters calculated in Equation (2).

$$d = \sqrt[4]{\frac{P_T G_T^2 G_t^2 \lambda^4 X^2 M}{P_R (4\pi)^4 \theta^2 B^2 F_2}} \tag{2}$$

Where P_R: reflected power received $[W]$, θ: the gain penalty, B: the path loss due to blockage, P_T: reader transmitted power $[W]$, G_t: tag antenna gain, G_T: transmitter antenna gain, λ: signal wavelength $[m]$, X: polarization mismatch, F_2: the fade margin for monostatic, and M: modulation factor (26).

An experiment was carried out to investigate how RSSI relates to the distance between 3 distinct readers and a single tag. The findings indicated a non-linear correlation and data uncertainties, particularly pronounced when the tag was located 50 cm below the bottom surface of ceiling-mounted readers, as illustrated in **Figure 1**.

Regarding uncertainty, elements like RF polarization (27) or interactions of RF waves can lead to RSSI fluctuations during distance measurement. These variations accumulate errors during triangulation calculations (28), ultimately reducing the accuracy of RSSI-based localization. Several enhancement methods have been proposed to improve accuracy. This includes employing semi-supervised learning to monitor shifts in signal distribution (29), utilizing trilateration that incorporates multiple measurements via Wi-Fi, and round trip time (RTT) in conjunction with the PoseNet categorization learning approach (30), or using device-assisted methods for motion tracking (31). Despite these advancements in location accuracy, including techniques like triangulation (8) and phase analysis (7),

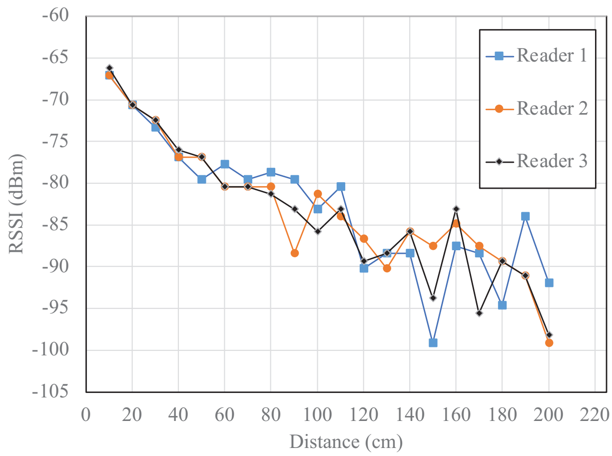

FIGURE 1 | RSSI variation relative to distance measurements.

challenges remain in achieving precise measurements consistently.

Range-free method

With the increasing computational power of digital microchips, electrical transponders have significantly decreased in size and cost, allowing them to be integrated into consumer-grade devices. These technological advancements have enabled researchers to investigate the distribution of electromagnetic fields across a network of transmitters and transponders. Looking at the LANDMARC system (32, 33), it pioneered the concept of reference tag fields, significantly improving the accuracy of indoor positioning. Through practice, the K-Nearest Neighbors (KNN) algorithm, researchers have developed a path loss model which effectively minimizes the errors (34). In addition, using the nonlinear backscattering method, it is helping passive devices to achieve high-precision instant 3D indoor positioning, with a median error is only 3.5 cm (35). Together, these innovations are representing a big advancement in the localization technology and underscore the potential to more precisely track in an indoor environment.

To overcome the challenge of using RSSI for distance-based localization, this study is adopting a range-independent approach and focusing on determining whether a tagged object is lying within the coverage of a specific reader in the room. By shifting the emphasis from distance measurement to RF sensing boundary, it ensures the reliable detecting of tags in the designated area. To solve the interference which caused by multipath propagation, the direct path RSSI is prioritized as the primary signal, enabling identifying of reader that capture the strongest signal and facilitate accurate room-level localization without needing complex calculations. Additionally, RSSI statistical analyses are used to define a virtual room boundary through a change point, simplifying the localization process and improving both speed and efficiency. This comprehensive strategy is providing a practical and effective solution for ensuring reliable indoor localization.

Methodology

The study began with small-scale laboratory experiments using limited RFID resources and later advanced to field tests in a public office to assess the system's practicality. Each room or designated area was equipped with an RFID reader to enable accurate occupancy detection. In ideal conditions, a single reader would detect signals from the corresponding tag. However, in real-world indoor environments, overlapping radio frequency detection zones often result in multiple readers capturing the same signal simultaneously. This issue becomes even more pronounced in crowded neighboring areas, as illustrated in **Figures 2a** and **b**. Through these experiments, the challenges of real-world deployment were systematically analyzed to refine the system's performance.

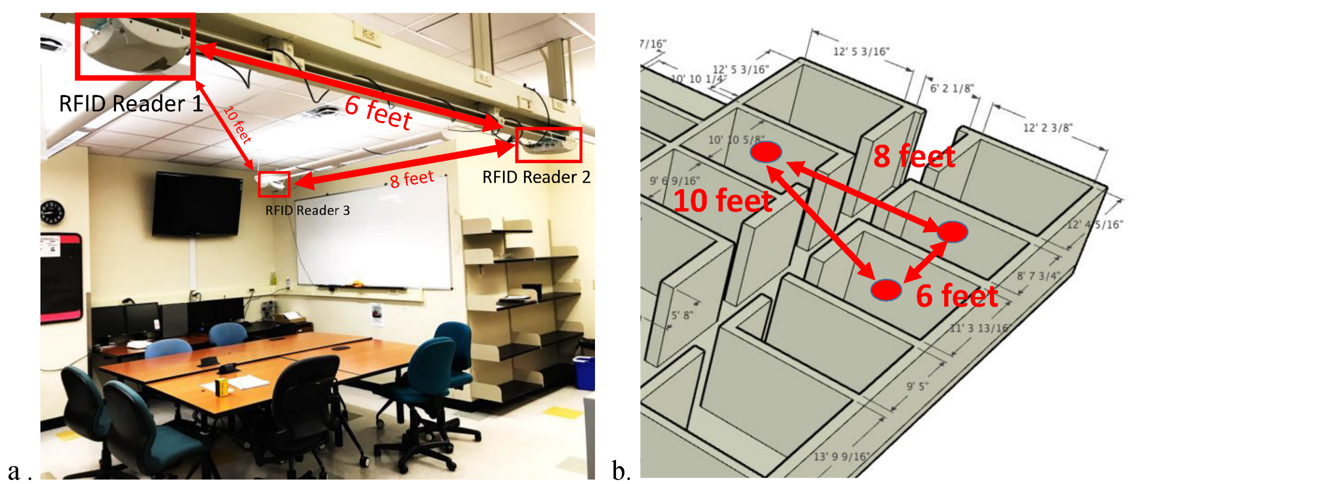

FIGURE 2 | (a) Placement of readers in the experimental office area. (b) Placement of readers in the experimental public rooms.

Passive RFID tag and reader

The experiment involved the use of ISO18000-6C EPC Class 1 Gen 2 passive RFID tags, which operate within the 860–960 MHz frequency range. These RFID tags were chosen for their affordability, priced below a quarter of a U.S. dollar each. Their compact size, measuring 73.5 mm by 21.2 mm with a microchip thickness under 1 mm, makes them highly portable and popular for widespread applications. Each tag comprises 3 core elements: a microchip, an inductive circuit, and a dipole-end load. As passive devices, they rely on the energy from the reader's signal to emit an ID signal intermittently. The reader's antenna charges the electricity capacitor and powers the microchip to facilitate this process.

For the experiments, an Alien ALR-9650 UHF reader was selected due to its compatibility with the RFID tags. This reader features a polarized antenna and houses an integrated microcontroller within a compact unit of 23.2 cm × 22.9 cm × 5.1 cm, making it ideal for ceiling installations. Additionally, the reader supports Power over Ethernet (PoE), allowing it to both receive power and transmit data via a single cable, improving its efficiency and versatility in various environments.

Anti-collision and anti-jamming algorithm

In standing RFID systems, the reader faces a bandwidth limitation, which hinders its ability to simultaneously detect multiple transponder signals. When multiple data signals overlap within the same bandwidth, the reader becomes confused, making it hard to differentiate between signals that start simultaneously. To solve this issue, an anti-collision mechanism is used, which is processed by readers before detection (36). A commonly employed anti-collision method is the binary tree-based slotted ALOHA protocol. In this approach, time is segmented into discrete slots, with each tag receiving a unique identification code (37). With this algorithm, the reader is dividing the time into the time slot and giving a unique identification number (ID) for each tag, organizing the identification process more efficiently by using the binary tree structure.

The slotted ALOHA algorithm, which is a method for efficiently identify RFID tags, can be mathematically represent as follows: Given a system with N transponders, each has a unique identifier, and the algorithm proceeds in 3 steps:

1. Begins:

The reader broadcasts an initial query to all tags, signaling them to respond in the first time slot.

2. Response:

After receiving the query, each tag is randomly delaying its response and then transmitting its unique identifier in the assigned time slot.

3. Collision Resolution:

If multiple tags respond in the same time slot, a collision has occurred. To resolve this, the reader uses a binary tree structure to identify each colliding tag individually.

The slotted ALOHA algorithm, which is a clever technique using binary trees, effectively minimizes the conflict and ensures the unique identification of every tag's response. To enhance system performance, we devised an anti-interference algorithm inspired by solutions for wireless communication challenges. This algorithm is addressing the potential interference which is caused by tag signals in the RFID system.

At the key of this solution is a duplicate ID filter. The filter is monitoring the incoming tag responses, storing their IDs and the RSSI value in the buffer. Then, the moving average calculation is applied on the RSSI values for every ID, which provides a reliable reference for future comparison.

When a new tag response has arrived, the system is cross-referencing its ID with an entry in the temporary buffer. If a match is found, it signals a potential duplicate ID, which indicates the possible interference. To solve this issue, the algorithm is comparing moving average RSSI values of tags that have duplicate IDs. The outliers in those values, which are often caused by weak signals or interference, are identified and excluded from the moving average calculation. This filtering process not only enhances the accuracy of interference detection but also significantly reduces computational overhead.

Experiment

Change-point detection

RSSI is playing a crucial role for identifying the transition point between RFID readers and establishing the virtual boundaries to demarcate the adjacent area. When an RFID tag is transitioned from one reader's coverage to another, a decrease in RSSI is observed on the former reader, while a corresponding increase is noticed on the latter one. This change point is serving as a virtual boundary, distinctly separating the different zones or rooms.

Figure 3 illustrates the application of the change point algorithm in an RFID setting. In this scenario, an RFID tag, symbolized by an arrow, moves at a constant speed of 4 cm/s between 2 RFID readers. The tag's journey commences at time 0 and spans 60 s, with the tag positioned 100 cm above reader 1. As the tag moves towards reader 2, the system

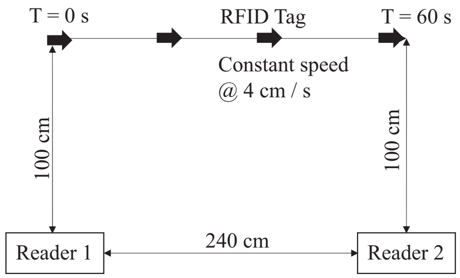

FIGURE 3 | Setup for detecting RSSI change-points.

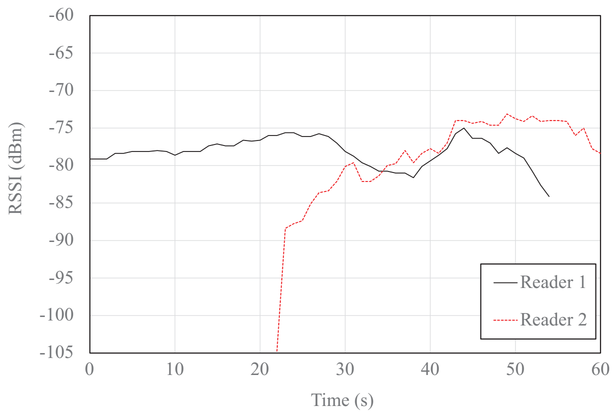

FIGURE 4 | RSSI readings from 2 adjacent readers as the tag moves.

records a gradual decline in RSSI on reader 1, accompanied by a simultaneous increase on reader 2. This pattern of RSSI fluctuations clearly delineates the virtual boundary between the 2 readers.

At approximately the 34-s mark, **Figure 4** reveals a critical intersection where the signal strengths of the 2 readers converge, suggesting a possible change in the tag's position. Notably, from 30 to 45 s, both readers show a consistent decline in RSSI readings. This decline in signal strength can be attributed to several factors:

1. Multipath and Diffraction:

When RF waves interact with obstacles like metal poles or building corners, they undergo reflections and diffractions, leading to multipath effects. These effects cause the signal to travel along multiple, often indirect, paths. The indirect paths disrupt the direct communication link between the RFID tag and reader, causing phase differences that result in interference. This interference can lead to signal attenuation or cancellation, creating "zeros" in certain areas of the read field, ultimately lowering the RSSI.

2. Reflection and Absorption:

Materials such as hidden wooden or metal strips within walls can reflect or absorb RF waves, weakening the signals. This interaction causes the signals received by both readers to be diminished as the energy of the waves is either redirected or absorbed by the surrounding environment.

Given the complexity of electromagnetic wave behavior and its sensitivity to environmental factors, which can introduce uncertainty in distance measurements, we designed an anti-interference algorithm. This algorithm identifies the strongest RSSI signals between the RFID reader and tag, ensuring more accurate distance calculations. Furthermore, the effectiveness of using RSSI for detecting the location of objects in nearby areas was confirmed through the RSSI change point detection test.

Server design and dataflow

The data acquisition system was developed using NI LabVIEW, a graphical programming tool that enables seamless communication with the RFID reader through assigned IP addresses and ports. The libraries in LabVIEW include Internet modules designed specifically for this purpose. To ensure accurate data recording, we implemented an instant pooling algorithm that centrally timestamps each detected RFID tag. The collected data is then combined with the location of each reader and forwarded to the low-congestion queuing processor.

In the software, each reader and writer is assigned a dedicated queue, which is subsequently merged into a main pool for anti-interference via a pooling mechanism. **Figure 5** demonstrates the flow of data for an RFID tag, showing how it follows the anti-collision protocol. Within a dynamic interval of under 1 s, the reader sends a packet, including the tag ID and RSSI value, to the server over the Ethernet network. Each reader operates autonomously, transmitting its packets independently. Upon receiving the data, the server designates a port and module for each incoming connection,

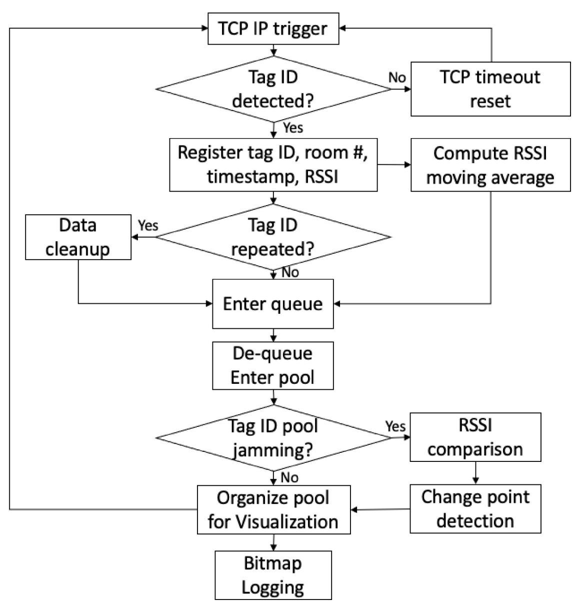

FIGURE 5 | Flowchart of the tag ID dataflow.

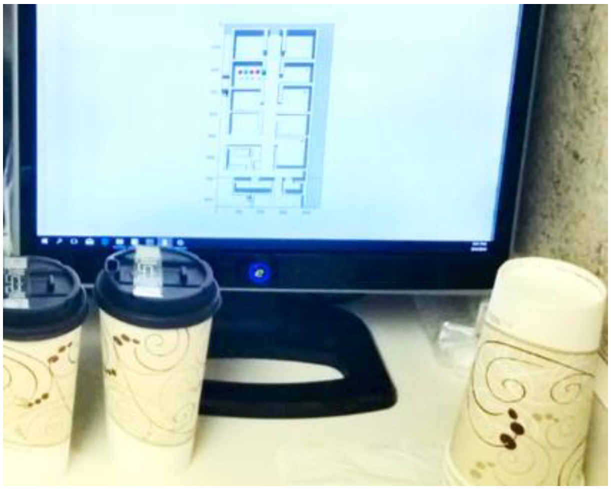

FIGURE 6 | RFID-tagged cup tracking in the office experiment.

corresponding to the specific area being monitored by the RFID system.

Parallel computation and anti-jamming process

To enhance the efficiency of tag conflict resolution, the task was initially assigned to each reader's computer, rather than relying solely on the server's central processor. The next step involves the server employing multi-threading modules that operate in parallel, handling data from several incoming ports simultaneously. When data is received at a specified port, the module identifies the corresponding ID and RSSI set, storing them in designated cache slots. During this process, centralized timestamps are applied to each ID set.

These cache slots serve multiple functions: filtering out duplicate or corrupted data, calculating the moving average of RSSI values, and synchronizing the queues. Each module operates independently, with its own clock, adhering to the first-in-first-out (FIFO) protocol. Once the data is processed, all modules compile their ID sets into queues for the anti-jamming process. A major challenge in this system is interference, which is addressed in the Methods section. After dequeuing the sparse data into a central counter-shading pool, we apply a change-point algorithm to pinpoint the ID set's location by refining its RSSI data.

Real-time display

The processed and aggregated tag data is stored in a web-based storage system to facilitate real-time visualization of each tag's location. A Python script can then retrieve this data and plot the tag locations on a floor map. The visualization can include additional details such as the tag's ID, ID group, free time, icon design, and other relevant information. Furthermore, system terminals can access the aggregated data via the cloud, enabling quick retrieval of information from anywhere in the world.

Real-world practice

A field trial was conducted to track the movement of coffee cups equipped with RFID tags. Office staff participated by carrying labeled cups for a designated period of time, allowing us to evaluate the system's performance in a real-world setting compared to the original laboratory setup. After repeated experiments to improve the system, we successfully tracked the tagged coffee cups, as shown in **Figure 6**. The coffee cup's location was accurately tracked, demonstrating the system's effectiveness in a real-world environment.

Results

Visualization

A bird's-eye view of a typical office, with 3 interconnected rooms, is visualized on the front-end interface of the RFID system. To avoid confusion during interruptions, only 1 room's label markers are displayed at a time. The anti-interference system effectively prevents multiple readers from detecting the same tag signal, ensuring accurate tag position identification. Distinctive icons, varying in color and shape, represent different states. These icons can also incorporate label names, object group symbols, and color codes to signify specific durations. As depicted in **Figures 7a** and **b**, fluctuations in the number of tracked objects, their locations, and the duration of room occupancy over a specific time range are illustrated through updates.

Dashboard monitor

A dashboard diagram is illustrated in **Figure 8**, where each block corresponds to an object. A table listing registered tags is positioned next to the yellow bar. Upon receiving a tag signal, the system determines the tag's location and initiates the tracking of its dwell time, represented by the length of the yellow bar. This dashboard facilitates accurate monitoring of room occupancy.

During the recording process, historical tag data is transformed into bitmap footprints, allowing for the tracking of each object's movement. The real-time dashboard then displays the current status of these objects. **Figure 9** shows the raw data for each tag, with RSSI readings represented as grayscale squares; lighter shading corresponds to stronger and closer signals. A 3×100 grayscale bitmap forms a long rectangular box. The horizontal axis represents 10-s intervals, while the vertical axis is divided into 3 rows, each

a. b.

FIGURE 7 | Live visualization of room occupancy.

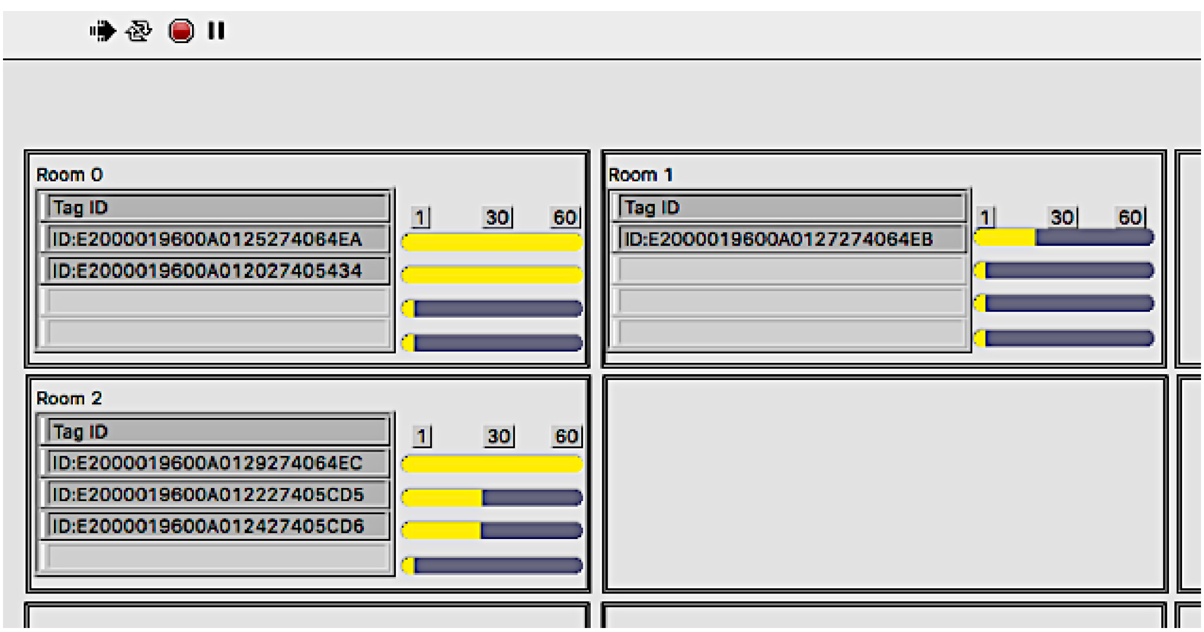

FIGURE 8 | Dashboard displaying ID status and duration of stay.

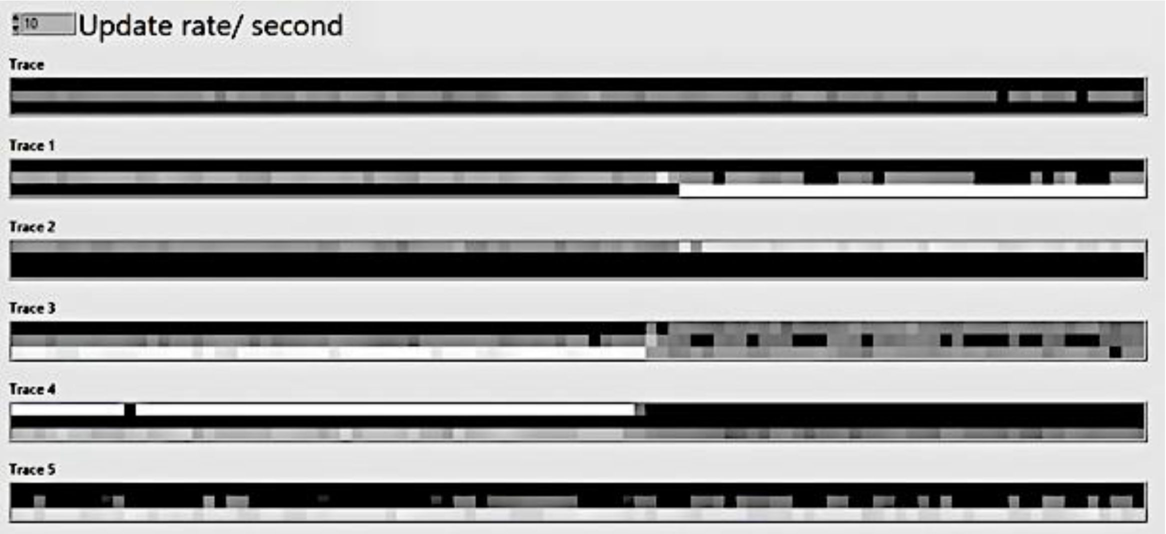

FIGURE 9 | Bitmap footprint dashboard showing raw data.

FIGURE 10 | (a) Raw footprint of tracked objects. (b) Footprint of tracked objects post anti-jamming process.

FIGURE 11 | Anti-jamming footprint dashboard for tracked objects.

corresponding to one of the 3 reading rooms. This dashboard uses 100-bit squares to visually illustrate how the reader detects tag signals over a 500-s period.

Figure 10a graphically illustrates the interference rejection process. After 250 s, the label transitions from Room 2 to Room 3, resulting in a distinct original transition in the center of the bitmap. Although Room 3 showed stronger RSSI readings after the conversion, Room 1 continued to record weaker RSSI signatures along the path. To solve this problem, the anti-interference system identifies the strongest signal among all readers, identifying Room 3 as the most likely location of the tag, as shown in Figure 10b.

Finally, Figure 11 shows the footprint dashboard showing all tracked objects, designed to ensure that each tag is only visible in 1 room at any given time. For example, Track 1 shows the movement of an object from Room 2 to Room 3, while Track 4 shows the transition of an object from Room 1 to Room 3 and did not return to Room 1.

Discussions

Looking at Table 1, it offers an analysis of factors impacting RFID system installation time, highlighting the pros and

TABLE 1 | Installation of 3 RFID readers system.

Condition	Advantage	Disadvantage	Install time (h)
With LF RFID system	Lower reader price	Active scanning from the user	1
With UHF RFID system	Rapid bulk scanning	Higher reader price	1
With Power supply	Lower router price	Scarcity of power slugs for the power supply in the ceiling	3
With POE supply	Rapid hardware deployment	Higher router price	0
With RF blocker	Lower computation power	Challenging to add metal walls in public rooms	5
With virtual boarder	Rapid hardware deployment	Higher computation power	0

FIGURE 12 | Aluminum RF blocker sheets installed on room walls.

cons of each condition. The final trial demonstrated much greater efficiency, with 3 card readers installed on the ceiling and connected via Ethernet in just 1 h. Emphasis is placed on optimizing indoor room positioning, with interference-resistant passive RFID systems being essential.

Standard power supplies are cost-effective, and the router is cheaper, but the lack of power in the ceiling created installation challenges, resulting in a time of about three h. In contrast, POE power supplies enable faster deployment, avoiding delays, but incur higher router costs. The first two rows of the table compare LF RFID and UHF RFID systems, while subsequent rows evaluate various power supply options. In the initial experiment, which did not use POE or virtual borders, installation took an additional 8 h.

Installing, adjusting, and testing RF blockers can take up to five h, primarily due to the difficulties associated with placing metal walls in public spaces, as illustrated in **Figure 12**. While RF blockers demand less computing power, the installation process is time-consuming. In contrast, virtual perimeters allow for rapid deployment of hardware with no installation time, despite requiring greater computing power. The hardware selected ensures fast and efficient deployment, highlighting the importance of using interference-resistant passive RFID technology for high-performance indoor room positioning.

The proposed RFID-based indoor positioning method demonstrates significant potential for generalization across various applications and environments. While initially tested in an office setting for tracking coffee cups, the system's core principles of rapid deployment, interference resistance, and room-level accuracy can be adapted to meet diverse needs. In healthcare facilities, for instance, the system could be scaled to track medical equipment and monitor patient movement across multiple wards, with the anti-jamming algorithm particularly valuable in environments with dense medical equipment. For warehouse applications, the ceiling-mounted reader configuration could be modified to accommodate higher ceilings and larger spaces, while the change-point detection algorithm could be enhanced to handle more complex movement patterns. The system's modular architecture and cloud-based visualization platform make it particularly adaptable to smart building implementations, where it could be integrated with existing building management systems for occupancy monitoring and energy optimization. The cost-effectiveness of passive RFID tags and the efficiency gains from PoE deployment remain advantageous across these applications, though considerations would need to be made for specific environmental challenges such as signal interference from metallic structures or the need for extended read ranges in larger spaces.

Conclusion

This research is presenting a novel approach to indoor localization by utilizing passive RFID technology, which addresses critical challenges in signal interference and rapid deployment. The proposed system is demonstrating significant advancements in 3 primary dimensions:

Firstly, the developed anti-interference algorithm effectively mitigates the multipath propagation and signal overlap issues, enabling more reliable room-level object tracking. By implementing a sophisticated change-point detection method and duplicate ID filter, the system achieves remarkable precision for distinguishing tag location across adjacent space.

Secondly, the research introduces a cost-effective and scalable solution for indoor positioning. Using UHF passive RFID tags priced under $0.25 USD and the ceiling-mounted readers, the system provides an economically viable alternative for complex positioning technology. The PoE implementation is further enhancing deployment efficiency, reducing installation time from eight h to just one h.

Thirdly, the cloud-based visualization platform represents a significant technological innovation. Through real-time dashboard and bitmap footprint tracking, the system offers unprecedented transparency in object movement and room occupancy. The ability to access the tracking data globally highlights the system's potential for widespread application in various environments.

Future research shall focus on further expanding system adaptability to more complex architecture configuration. Notwithstanding the current achievement, the continuous technological optimization has remained imperative for advancing indoor localization technology.

Conflicts of interest

The authors declare that the research has no conflicts of interest.

Funding

The authors declare that the research has no funding.

References

1. Wan HD, Gonnuru VK. Disassembly planning and sequencing for end-of-life products with RFID enriched information. Robot Comput Integr Manuf. (2013) 29(3):112–8.
2. Xu J, Li Z, Zhang K, Yang J, Gao N, Zhang Z, et al. The principle, methods and recent progress in RFID positioning techniques: a review. *IEEE J Radio Freq Identif.* (2023) 7:50–63.
3. Li C, Mo L, Zhang D. Review on UHF RFID localization methods. *IEEE J Radio Freq Identif.* (2019) 3(4):205–15.
4. Canals A, Josephy P, Tanner S, Wattenhofer R. Robust indoor localization with ADS-B. *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking.* ACM (2021). p. 505–16.
5. Masyuk MA. Information security of RFID and NFC technologies. *J Phys Conf Ser.* (2019) 1399(3):033093.
6. Landaluce H, Arjona L, Perallos A, Falcone F, Angulo I, Muralter F. A review of IoT sensing applications and challenges using RFID and wireless sensor networks. *Sensors.* (2020) 20(9):2495.
7. Mo LF, Zhu YJ, Zhang DK. UHF RFID indoor localization algorithm based on BP-SVR. *IEEE J Radio Freq Identif.* (2022) 6:385–93.
8. Kim J, Bang J, Choi A, Moon HJ, Sung M. Estimation of occupancy using IoT sensors and a carbon dioxide-based machine learning model with ventilation system and differential pressure data. *Sensors.* (2023) 23(2):585.
9. Fang Y, Cho YK, Zhang S, Perez E. Case study of BIM and cloud-enabled real-time RFID indoor localization for construction management applications. *J Constr Eng Manag.* (2016) 142(7):05016003.
10. Costin A, Teizer J. Utilizing BIM for real-time visualization and indoor localization of resources. In: *Computing in Civil and Building Engineering (2014).* American Society of Civil Engineers (2014). p. 649–56.
11. Costin AM, Teizer J. Fusing passive RFID and BIM for increased accuracy in indoor localization. *Vis Eng.* (2015) 3(1):17.
12. Guerrieri JR, Francis MH, Wilson PF, Kos T, Miller LE, Bryner NP, et al. RFID-assisted indoor localization and communication for first responders. *2006 First European Conference on Antennas and Propagation* (2006). p. 1–6.
13. Wang J, Dhanapal RK, Ramakrishnan P, Balasingam B, Souza T, Maev R. Active RFID based indoor localization. *2019 22th International Conference on Information Fusion (FUSION).* IEEE (2019). p. 1–7.
14. Sunhong P, Shuji H. Indoor localization for autonomous mobile robot based on passive RFID. *2008 IEEE International Conference on Robotics and Biomimetics.* IEEE (2009). p. 1856–61.
15. Zhao J, Xue F, Li D-A. Intelligent management of chemical warehouses with RFID systems. *Sensors.* (2019) 20(1):123.
16. Jae Sung C, Byung Rak S, Hee Kuk K, Dong Ha L. Indoor localization of unmanned aerial vehicle based on passive UHF RFID systems. *2012 9th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI).* IEEE (2012). p. 188–9.
17. Whitney AM, Parker JM, Kratzer ZC, Fessler JT, Whitney JG. Reducing RF distance error by characterizing multipath. *IEEE Trans Instrum Meas.* (2018) 68(9):3329–38.
18. Athalye A, Savic V, Bolic M, Djuric PM. Novel semi-passive RFID system for indoor localization. *IEEE Sens J.* (2013) 13(2):528–37.
19. Abdulghafor R, Turaev S, Almohamedh H, Alabdan R, Almutairi B, Almutairi A, et al. Recent advances in passive UHF-RFID tag antenna design for improved read range in product packaging applications: a comprehensive review. *IEEE Access.* (2021) 9:63611–35.

20. Obeidat H, Shuaieb W, Obeidat O, Abd-Alhameed R. A review of indoor localization techniques and wireless technologies. *Wirel Pers Commun.* (2021) 119(1):289–327.
21. Boontrai D, Jingwangsa T, Cherntanomwong P. Indoor localization technique using passive RFID tags. *2009 9th International Symposium on Communications and Information Technology*. IEEE (2009). p. 922–6.
22. Zhou J, Zhang H, Mo L. Two-dimension localization of passive RFID tags using AOA estimation. *2011 IEEE International Instrumentation and Measurement Technology Conference*. IEEE (2011). p. 1–5.
23. Chen X, Xie L, Wang C, Lu S. Adaptive accurate indoor-localization using passive RFID. *2013 International Conference on Parallel and Distributed Systems*. IEEE (2013).
24. Makki A, Siddig A, Saad M, Cavallaro JR, Bleakley CJ. Indoor localization using 802.11 time differences of arrival. *IEEE Trans Instrum Meas.* (2015) 65(3):614–23.
25. Mrindoko NR, Minga LM. A comparison review of indoor positioning techniques. *Int J Comput.* (2016) 21(1):42–9.
26. Griffin JD, Durgin GD. Complete link budgets for backscatter-radio and RFID systems. *IEEE Antennas Propag Mag.* (2009) 51(2):11–25.
27. Paolini G, Masotti D, Antoniazzi F, Cinotti TS, Costanzo A. Anchorless indoor localization and tracking in real-time at 2.45 GHz. *2019 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE (2019).
28. Liu X, Peng J, Liu T. A novel indoor localization system based on passive RFID technology. *Proceedings of 2011 International Conference on Electronic & Mechanical Engineering and Information Technology*. IEEE (2011). p. 4285–8.
29. Ghourchian N, Allegue-Martinez M, Precup D. Real-time indoor localization in smart homes using semi-supervised learning. *Twenty-Ninth IAAI Conference*. (2017).
30. Raza A, Lolic L, Akhter S, Liut M. Comparing and evaluating indoor positioning techniques. *2021 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*. IEEE (2021).
31. House S, Connell S, Milligan I, Austin D, Hayes TL, Chiang P. Indoor localization using pedestrian dead reckoning updated with RFID-based fiducials. *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE (2011).
32. Ni LM, Liu Y, Lau YC, Patil AP. LANDMARC: Indoor location sensing using active RFID. *Proceedings of the First IEEE International Conference on Pervasive Computing and Communications, 2003.(PerCom 2003)*. IEEE (2003). p. 407–15.
33. Guang-yao J, Xiao-yi L, Myong-Soon P. An indoor localization mechanism using active RFID tag. *Proceedings of the IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing – Vol 1 (SUTC'06)*. IEEE (2006). p. 40–3.
34. Dao TH, Nguyen QC, Ngo VD, Le MT, Hoang CA. Indoor localization system based on passive RFID tags. *2014 5th International Conference on Intelligent Systems, Modelling and Simulation*. IEEE (2014).
35. Ma Y, Hui X, Kan EC. 3D real-time indoor localization via broadband nonlinear backscatter in passive devices with centimeter precision. *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking*. ACM (2016).
36. Sanchez L, Ramos V. An EPC class-1 generation-2 anti-collision protocol for RFID tag identification in augmented systems. *2015 International EURASIP Workshop on RFID Technology (EURFID)*. (2015). p. 36–43.
37. Pal K. Algorithmic solutions for RFID tag anti-collision problem in supply chain management. *Proc Comput Sci.* (2019) 151:929–34.