A Comprehensive Survey on Industrial RFID Localization: Methods, Integrated Technologies, Applications and Future Directions

Mehdi Naseh, Arash Bozorgchenani, *Member, IEEE,* Davide Dardari, *Fellow, IEEE,* Nima Bagheralmousavi, Amir Reza Dastkhosh, Bruno Quoitin, Véronique Moeyaert, *Member, IEEE,* Haris Pervaiz, *Member, IEEE,*

***Abstract*—The technology known as Radio Frequency Identification (RFID) has become a vital part of industrial localization, with applications ranging from asset management to logistics, autonomous navigation, vehicle localization, and product traceability, to name a few. This survey provides a comprehensive overview of RFID-based localization methods, categorizing them into fingerprinting, non-fingerprinting techniques, and hybrid tracking models which are used and combined with different localization techniques. The paper explores the integration of RFID with complementary technologies such as Internet of Thing (IoT), Wireless Sensor Networks (WSN), Simultaneous Localization And Mapping (SLAM), Light Detection And Ranging (LiDAR), Laser, and Synthetic Aperture Radar (SAR) demonstrating how these synergies enhance localization accuracy and system performance in various industrial contexts. Additionally, this study evaluates the performance of these methods based on key metrics such as system accuracy, coverage, cost, speed, and robustness. Challenges associated with RFID-based localization, including, scalability, and computational overhead, are discussed, alongside future directions, including the potential role of Ultra-wideband (UWB), mmWave technology, Digital Twins (DTs), Artificial Intelligence (AI), Augmented Reality (AR), and Reconfigurable Intelligent Surfaces (RIS) approaches in improving localization performance. This survey aims to serve as a resource for researchers and practitioners, providing insights into current advancements and guiding future innovations in RFID localization technologies.**

***Index Terms*—5G, 6G, Integrated Technologies, Positioning, RFID-based Localization, Industrial Localization.**

Mehdi Naseh is with the Electromagnetism and Telecommunications Department and Computer Science Department, University of Mons, 7000, Mons, Belgium. email:mehdi.naseh@umons.ac.be

Arash Bozorgchenani is with the School of Computer Science, University of Leeds, UK, email:a.bozorgchenani@leeds.ac.uk

Davide Dardari and Nima Bagheralmousavi are with the Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi", University of Bologna, Bologna, 40136, Italy, e-mail: Davide.Dardari@unibo.it, Nima.Bagheralmousavi@studio.unibo.it

Amir Reza Dastkhosh is with the Department of Electronic Science and Technology, the University of Science and Technology of China, Hefei, 230026, China, e-mail: amirreza@mail.ustc.edu.cn

Bruno Quoitin is with the Computer Science Department, University of Mons, 7000, Mons, Belgium, e-mail: bruno.quoitin@umons.ac.be

Véronique Moeyaert is with the Electromagnetism and Telecommunications Department, University of Mons, 7000, Mons, Belgium. email: veronique.moeyaert@umons.ac.be

Haris Pervaiz is with the School of Computer Science and Electronic Engineering, University of Essex, CO43SQ, Colchester, UK, e-mail: haris.pervaiz@essex.ac.uk

This research is supported thanks to BEL6GICA 6G project supported by FOD 'Economie, K.M.O., Middenstand en Energie' of Belgium.

I. Introduction

In today's rapidly evolving technological landscape, the ability to track and locate objects and people efficiently is more important than ever. A wireless technology that is widely utilized in many different applications is Radio Frequency Identification (RFID). RFID has emerged as a key player in this domain, offering a way to identify and track items using radio waves. RFID's importance lies in its versatility, low cost, and efficiency. It has significantly impacted various industries by enhancing processes such as asset tracking, product traceability, vehicle localization, and logistics management. For instance, in the retail sector, RFID tags help in managing inventory by providing real-time data on product locations. In healthcare, they assist in tracking equipment and monitoring patient movements, thereby improving service delivery and safety.

A. RFID Localization Paired with Integrated Technologies

As Internet of Things (IoT) continues to grow, connecting everyday objects to the Internet, RFID plays a critical role as a bridge between physical objects and digital systems. It enables seamless communication and data exchange, which powers services and applications like smart homes, Intelligent Transportation Systems, and automated manufacturing processes. RFID has become essential in these areas because, unlike traditional methods such as barcodes, it does not require direct visibility. This allows items to be scanned even when inside boxes or behind other objects, enhancing efficiency in warehouses and retail stores. Moreover, RFID tags can store more information and can be read much faster than barcodes. The IoT has made extensive use of RFID-based indoor localization solutions. Localization becomes increasingly important as the IoT develops to give service providers and customers access to accurate localization data anywhere, at any time [1], [2].

The network in charge of collecting, processing and sending wireless data to the designated database storage center is called Wireless Sensor Networks (WSN) [3]. In WSN, RFID serves as a key component for applications such as manufacturing, e-health, surveillance, and environmental monitoring. Although WSNs are not specifically designed for indoor localization, they leverage technologies like ZigBee and Real-Time Lo-

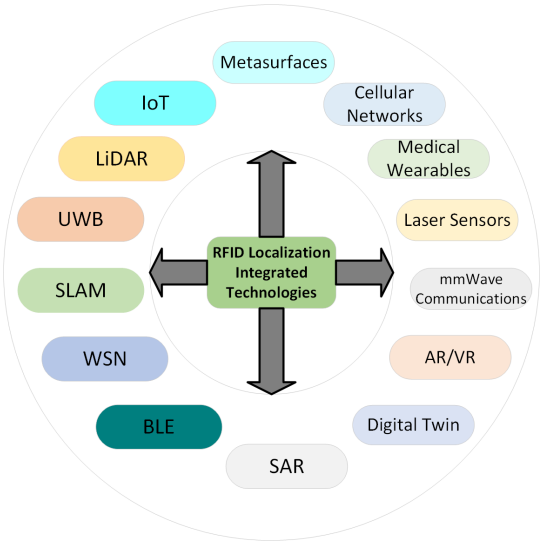


Fig. 1: RFID Localization Integrated Technologies

cating Systems (RTLS) with battery-powered tags to enable high-performance wireless sensing and localization [4], [5].

Various technologies such as Ultra-wideband (UWB), Simultaneous Localization and Mapping (SLAM), Synthetic Aperture Radar (SAR), are now commonly integrated with RFID systems to enhance localization and tracking. These technologies, which are shown in Fig.1, bring different advantages depending on the environment and application. SLAM is a system that integrates SLAM as a fundamental approach to surrounding sensing. Light Detection And Ranging (LiDAR) sensors, cameras, odometers, and Inertial Measurement Units (IMUs) are among the many sensor types it supports [6]. The quantity and location of LiDAR sensors determine the quality and volume of information that can be collected. A large number of LiDAR sensors must be distributed in order to lower the measurement limit [7]. For almost 30 years, earth remote sensing has made extensive use of SAR. For a wide range of applications, including geoscience and climate change research, environmental and earth system monitoring, 2D and 3D mapping, change detection, 4D mapping (space and time), security-related applications, it offers high-resolution, day-and-night, and weather-independent images [8]. Since SAR has evolved into a ubiquitous remote sensor that can be used for a range of missions, there is an increasing need on more quickly functioning SAR systems. Unmanned aerial vehicle-mounted SAR systems are anticipated to offer appropriate responses to these needs [9].

One more widely used piece of technology is UWB, which uses a wide range of frequencies in the gigahertz (GHz) spectrum to transmit data through extremely short pulses that last less than a nanosecond. This allows UWB systems to achieve very high localization accuracy, down to the *cm*-meter level. They are also highly resistant to interference (anti-jamming). However, these advantages relatively come with the downside of being expensive to build. The high construction costs can offset the benefits of their precision and reliability, making them less accessible for widespread use [10]. Moreover, consider that commercial systems operating at 2.4 GHz, such as UWB , along with the 5.8 GHz band, have become popular choices for RFID-based localization due to their affordability, ease of installation, and minimal maintenance requirements [11], [12]. Additionally, Bluetooth Low Energy (BLE) is a more power-efficient variant of Bluetooth that focuses on long battery life and low-power communications, like in wearable technology. Its most recent development, BLE 5.2, added a new PHY layer called BLE coded to increase the communication range to up to 1 kilometer, suggesting the possibility of supporting localization targets, ideal for both indoor and outdoor tracking applications [13], [14], [15].

Additionally, Multiple-input Multiple-output (MIMO) RFID systems have also been addressed to enhance the accuracy and performance of localization tracking [16]. Since UWB, mmWave, Digital Twins (DTs), Artificial Intelligence (AI), Augmented Reality (AR), and Reconfigurable Intelligent Surfaces (RIS) are the most intriguing and promising technologies for RFID localization in the future, they will all be discussed in the future directions section. Other integrated technologies, such as wearables, cellular technologies, and laser sensors, are also addressed in the survey of works and in other subsections. Each integrated technology can be deployed with either active or passive RFID tags (e.g., [17], [18]).

B. Key Contributions and Structure of the Survey

1) Key Contributions

In recent years, numerous survey articles have been published on RFID localization; however, many rely on outdated references. Currently, there is no standardized or widely accepted framework for evaluating the effectiveness of emerging technologies and methods in this domain. As a result, existing solutions are often assessed under inconsistent criteria tailored to specific scenarios. To address these limitations, this paper provides a new survey whose contributions are threefold.

First, the paper offers a unified analysis of integrated technologies for RFID localization, covering hybrid methods, localization algorithms, and their combination with WSN and IoT systems. Unlike prior works that focus on limited subsets (see Tab.I), this study systematically examines a broad range of technologies, evaluating their benefits, limitations, and suitability for real-world deployment.

Second, the paper presents a comprehensive and up-to-date review of future research directions, including emerging technologies such as mmWave, UWB, AI-based methods, DTs, AR, and RIS. In doing so, it highlights current gaps and challenges while outlining the potential of these technologies for next-generation RFID localization systems.

Finally, the survey is specifically focused on industrial RFID localization, providing practical insights into the applicability, scalability, and cost of different approaches. The analysis bridges academic developments and industrial requirements, offering guidance on selecting appropriate solutions for real-world applications. This paper provides an up-to-date analysis of RFID localization methods and integrated technologies, addressing gaps in existing surveys. As such, a new survey that not only reviews recent academic developments but also

examines their commercial implications in industrial RFID solutions is both timely and necessary.

A list of the most related and recent existing survey papers is presented in Tab.I, where we have highlighted our contribution. Tab.I summarizes the existing survey papers with a focus on different aspects of RFID localization. The surveys were selected based on several key criteria. We focused on surveys published between 2019 and 2024 to ensure the inclusion of the most recent advancements and developments in RFID localization. Although we considered high-quality conference papers and non-IEEE journals, surveys published in IEEE journals were given priority due to their high impact and rigorous peer-review process. Additionally, we chose surveys that not only summarize the current state of RFID localization but also identify areas where further research is needed. This includes pinpointing limitations, open challenges, and future directions in the field that have not yet been sufficiently addressed.

2) Exclusion and Inclusion Criteria

We acknowledge there exist excellent published RFID research papers in fields such as geoscience, medicine [24], or rescue and other topics [25], however, we choose not to include them in our survey paper as we concentrate on industrial RFID applications. Here are the exclusion criteria in our work

1) Journals that release letters, editorials, or notes,
2) Published works related to the chemical/ materials for RFID,
3) Non-industrial published research, e.g., in the area of geoscience and medicine,
4) Articles that solely discuss technology's financial elements,
5) RFID chipless papers and RFID tags with antenna on-chip,
6) Finally, the non-English-language papers.

We summarize our inclusion criteria below

1) Recent works that offer the most fruitful examination of RFID localization from industrial and practical perspectives,
2) Strong pure theoretical works in the field of RFID localization research,
3) Published papers for RFID localization supported by IoT and WSN,
4) Discussion-based articles on subjects like UWB, DT, AR, and AI-based localization that offer fresh ideas for RFID localization in the future.

The key contribution of our survey paper is listed below

1) This paper offers a thorough analysis of the various indoor localization applications that have been put out in the literature between 2008 and 2024, with a focus on products traceability, autonomous navigation, logistics management, user or asset tracking, and vehicular localization. We assess these areas by highlighting their advantages and disadvantages using a systematic approach.
2) This work provides a thorough analysis of several integrated technologies that can be used for indoor localization services, such as wearables, cellular, laser, WSN, LiDAR, SLAM, SAR, and others. In addition to classifying the existing technologies, we also used this method to compare related papers.
3) We discuss an evaluation framework that can be used to assess different localization algorithms. We outline localization algorithms into AI-based solutions, graph-based localization algorithms, Kalman Filter (KF), heuristic-based solutions, and Monte Carlo (MC) localization techniques that are useful for system design and assessments.
4) We display charts and tables, evaluate the surveyed works and provide statistical insights. We classify and analyze the published works in a variety of ways, including the best-obtained accuracy in the case of access technologies, achieved accuracy versus applied technologies, the percentage of applied RFID localization algorithms and qualitative comparison of RFID integrated localization technologies.
5) In light of the growing interest in UWB, mmWave, AI-driven , AR, DT, and RIS, we offer future directions and assess their suitability for RFID localization.

3) Survey Structure

The content of the paper is illustrated in Fig. 2 and structured briefly as follows:

- Section II: This section presents the fundamentals of Ultra-High Frequency (UHF) RFID, beginning with its operating principles, standards and specifications, key localization performance metrics, and major application areas. It then reviews position-related technologies, including Wireless Local Area Networks (WLANs), cellular networks, Wireless Sensor Networks (WSNs), and the Internet of Things (IoT), followed by an overview of RFID localization measurement techniques, including Received Signal Strength (RSS), Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), Phase Difference of Arrival (PDoA), and proximity-based methods. The section concludes with a summary of the key lessons learned.
- Section III: A range of localization methods are covered, including fingerprinting methods (such as Artificial Neural Networks (ANN), Support Vector Machine (SVM), K-Nearest Neighbor (KNN)), non-fingerprinting, fusion methods, and finally Bayesian tracking method (such as Exact Method (EM), Expectation Maximization Method (EMM), Variational Bayesian's EM (VBEM), Bayesian Hierarchical Appearance Model (BHAM), and Extended KF (EKF)).
- Section IV: This section surveys the related works. Our analysis methodology and evaluation framework consider a multitude of elements as well as the challenges associated with different technologies, localization algorithms, metrics, and procedures that are employed. We provide insights after surveying all these works by summarizing the lessons learned and showing some statistics in figures and tables.
- Section V: This section discusses emerging research challenges and future directions in RFID localization, including UWB RFID solutions, mmWave RFID solutions, AR-based localization using RFID, AI-based RFID

TABLE I: Comparison of Related Surveys on RFID Localization

Research	Integrated Technologies							Localization Algorithms					Future Research Directions						
	WSN	LiDAR	SLAM	SAR	Cellular	Laser	Wearable	Heuristic	KF	AI	MC	Graph-based	UWB	mmWave	AI-based	AR	Meta-surface	Digital Twin
[19]			✓			✓			✓									
[20]			✓						✓	✓								
[21]									✓	✓		✓						
[22]									✓									
[23]				✓					✓				✓		✓			
[Our]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

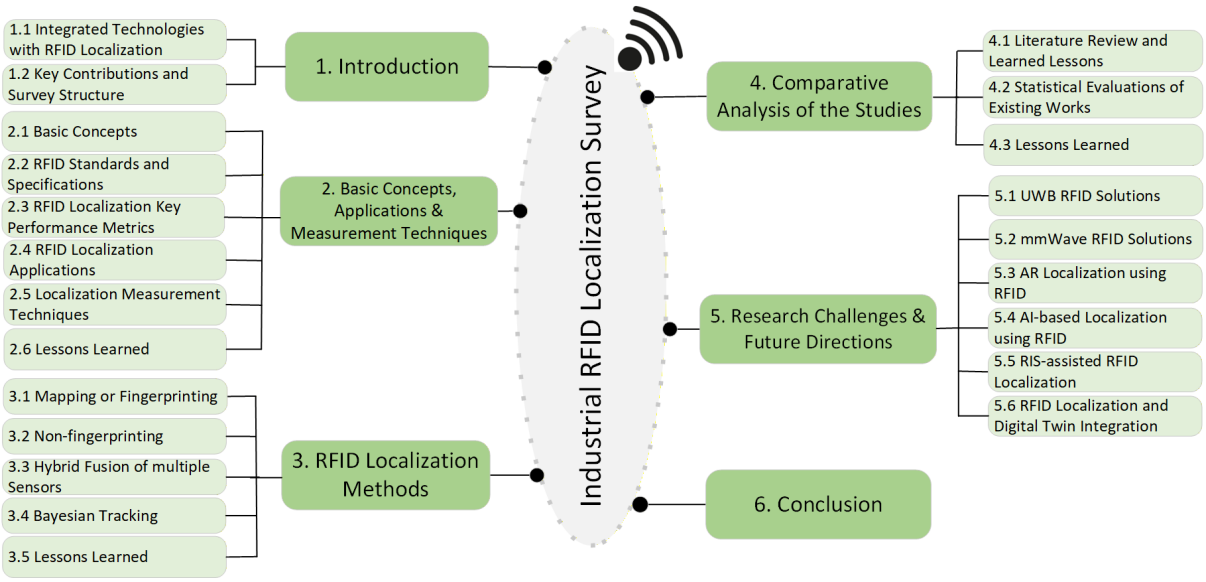


Fig. 2: Structure of the Survey

localization, RIS-assisted RFID localization, and the integration of RFID localization with DT technologies.

- Section VI: Finally, this section draws some conclusions.

We provide the glossary of the abbreviations used in this paper in Tab.II.

II. Basic Concepts, Applications and Measurement Techniques

A. Basic Concepts

An RFID system consists of three main components: RFID readers, RFID tags, and RFID middleware. RFID readers transmit radio waves to communicate with RFID tags, retrieving data stored on the tags by capturing signals reflected back [26]. RFID readers are typically larger and more expensive than tags, so in RFID-based localization, numerous tags are often deployed throughout an environment while a mobile reader gathers data. Alternatively, when readers are fixed, and tags are carried by the subjects, this setup becomes more effective for tracking a large number of subjects. RFID middleware acts as the software interface that manages data exchange and communication between readers and tags, ensuring smooth system operation.

RFID tags store data, typically in the form of an ID, and can be classified into three types: passive, active, and semi-passive. Active RFID tags contain an internal power source and can transmit data independently. Semi-passive tags also contain a battery but only transmit data when they detect a reader's signal. In contrast, passive tags rely entirely on the reader's signal for power and use backscatter modulation to reflect the reader's signal and send data back.

The distinction between active and passive RFID is fundamental to understanding RFID systems. Active RFID systems use battery-powered tags that continuously transmit signals, while passive RFID systems rely on backscatter communication. In a passive system, the reader powers the tag by emitting radio waves, and the tag reflects those waves back to the reader while encoding information. The passive RFID system incorporates an equivalent circuit model and backscatter modulation concepts, which emphasize the system's power harvesting functionality [27]. This power harvesting links the downlink to the backscatter uplink performance, determined by factors such as constellation selection and forward error correction. Passive RFID systems are often favored for their cost-effectiveness and ability to function without an internal power source, but they may have limitations in signal strength and range.

Backscatter communication systems can be categorized into three main types based on their architecture: monostatic,

TABLE II: Glossary of Used Abbreviations

Abbreviation	Description	Abbreviation	Description
AI	Artificial Intelligence	MLP	Multi-layer Perceptron
ANN	Artificial Neural Networks	MIMO	Multiple-input Multiple-output
AoA	Angle of Arrival	NFC	Near Field Communication
AR	Augmented Reality	NLoS	Non-Line of Sight
BHAM	Bayesian hierarchical appearance model	NN	Neural Networks
BLE	Bluetooth Low Energy	OFDM	Orthogonal Frequency-Division Multiplexing
BPSK	Binary-phase-shift keying	PDoA	Phase Difference of Arrival
CIR	Channel Impulse Response	PDP	Power Delay Profile
CSI	Channel State Information	PDF	Probability Density Function
CV	Computer Vision	RF	Radio Frequency
DT	Digital Twin	RFID	Radio Frequency Identification
EKF	Extended Kalman Filter	RMSE	Root Mean Square Error
ELM	Extreme Learning Machine	RSS	Received Signal Strength
EM	Exact Method	RSSI	Received Signal Strength Indicator
EMM	Expectation Maximization Method	RTLS	Real-Time Locating System
FD	Frequency Domain	SA	Synthetic Aperture
FMCW	Frequency-Modulated Continuous Wave	SAR	Synthetic Aperture Radar
GMSK	Gaussian Minimum Shift Keying	SD	Spatial Domain
GNSS	Global Navigation Satellite Systems	SLAM	Simultaneous Localization and Mapping
GPS	Global Positioning System	SMO	Sequential Minimal Optimization
IC	Integrated Circuit	SVM	Support Vector Machine
IMU	Inertial Measurement Unit	SVR	Support Vector Regression
IoT	Internet of Things	TD	Time Domain
IPS	Indoor Positioning System	TDoA	Time Difference of Arrival
IR	Infrared	ToA	Time of Arrival
KF	Kalman Filter	ToF	Time of Flight
KNN	K-Nearest Neighbor	UHF	Ultra-High Frequency
LiDAR	Light Detection and Ranging	UNB	Ultra-Narrow Band
LoS	Line of Sight	UWB	Ultra-Wideband
LPWAN	Low Power Wide Area Network	VBEM	Variational Bayesian Exact Method
MAE	Mean Absolute Error	VLC	Visible Light Communication
MC	Monte Carlo	WLAN	Wireless Local Area Network
ML	Machine Learning	WPAN	Wireless Personal Area Network
MSE	Mean Squared Error	WSN	Wireless Sensor Networks

bistatic, and ambient backscatter communication systems. In monostatic systems, the transmitter and receiver are co-located, meaning the same device emits the signal and receives the backscattered signal from the tag. Bistatic systems, on the other hand, have separate devices for transmitting and receiving, allowing for greater flexibility in placement and range. Ambient backscatter systems utilize ambient signals already present in the environment, such as TV or Wi-Fi signals, to enable communication without the need for a dedicated power source [28]. In [29] a detailed description of inter-technology backscatter for implanted devices demonstrates how ZigBee and Wi-Fi signals can be generated using backscatter techniques. These approaches show the effectiveness of single sideband backscatter, which further enhances the versatility of RFID systems. Furthermore, [30] explains that the core principle of backscatter involves electromagnetic waves modulated by a backscatter tag, which transmits backscatter signals that are then demodulated by the receiver. Additionally, the relative orientation of the reader and tag antennas not only affects the distance between them but also introduces a phase shift in the backscattered UHF RFID signal. Studies such as [31] have explored this phase shift, introducing a time-varying phase offset to mitigate its effects.

Electronic product code parameters refer to a standardized identification system used in UHF RFID systems, where each tag is assigned a unique code. These parameters help facilitate communication and ensure interoperability between RFID systems. In UHF RFID systems, electronic product code parameters are often coupled with probabilistic tag detection models to enhance localization accuracy [19] These models use metrics such as travel time, Received Signal Strength Indicator (RSSI), and phase to assess the RFID tag location. Efforts to achieve greater accuracy in localization have also led to innovations such as energy-autonomous tags, which operate efficiently with minimal reliance on external power. One notable advancement in this field is the integration of cutting-edge localization techniques with the principles of RFID backscatter modulation, enabling more precise tracking and communication in various environments [10].

B. RFID Standards and Specifications

RFID technology operates across three primary frequency bands, each offering distinct characteristics in terms of operating range, data rate, and environmental suitability.[1]

Low Frequency RFID operates at 125–134.2 kHz and typically provides read ranges below 10 cm with relatively low data transfer rates. However, its ability to operate reliably around liquids and metallic objects makes it well suited for applications such as animal identification and access control.

High Frequency RFID operates at 13.56 MHz and offers read ranges of up to approximately 1 m with moderate data transfer rates, making it suitable for applications including contactless payments, ticketing, and electronic passports. Near Field Communication (NFC), an extension of HF RFID, operates at the same frequency and supports both one-way and two-way communication, enabling secure peer-to-peer interactions while maintaining a typical operating range of only a few centimetres.

[1]Low Frequency RFID is standardised under ISO/IEC 18000-2 and ISO 11784/11785; High Frequency RFID under ISO/IEC 14443 and ISO/IEC 15693 (including NFC); and UHF RFID under ISO/IEC 18000-63 together with the GS1 EPC Gen2 protocol.

UHF RFID operates between 860 and 960 MHz and provides significantly longer read ranges, reaching up to 12 m for passive tags, together with high-speed identification of multiple tags simultaneously. However, UHF signals are more susceptible to attenuation by liquids and reflection from metallic surfaces, which can affect system performance in challenging environments.

Compared with LF and HF RFID, which prioritise reliable operation, signal stability, security, and short-range precision, UHF RFID is designed to maximise read range, throughput, and scalability. These characteristics make UHF particularly suitable for applications such as large-scale inventory management, asset tracking, and supply chain monitoring, where numerous passive tags can be identified simultaneously over relatively long distances without requiring an onboard power source.

C. RFID Localization Key Performance Metrics

While accuracy is paramount in evaluating indoor RFID localization, it is not the sole benchmark for performance. Accuracy is defined as the proximity of an estimated coordinate to an object's true position at any given moment. However, due to the wide diversity of existing localization systems, applying a singular definition or metric is impractical. Consequently, researchers typically assess these systems using a broader set of criteria, including, but not limited to, accuracy, coverage, reliability, robustness, cost and speed.

Greater coverage facilitates the deployment of an indoor RFID localization system across expansive environments while minimizing the required number of emitters Robustness refers to a system's ability to maintain operational integrity when subjected to environments that exceed standard or nominal parameters. Cost encompasses all financial expenditures associated with both the positioning hardware and the necessary supporting infrastructure. While frequently conflated in general usage, robustness and reliability serve as distinct performance metrics within the domain of RFID localization. Robustness characterizes a system's capacity to maintain operational integrity despite external stressors, such as environmental interference, hardware variability, or dynamic surroundings. Conversely, reliability pertains to long-term performance stability, evidenced by the repeatability of measurements, consistent system availability, and high confidence levels in the output data. Because accuracy is the fundamental benchmark for evaluating industrial RFID localization, it is the central focus of most research. Consequently, this study prioritizes accuracy as the primary metric, over and above other performance indicators.

D. RFID Localization Applications

RFID technology has emerged as a powerful solution to meet these needs, enabling real-time tracking and positioning without the need for manual intervention. By utilizing radio waves to automatically identify and monitor tags attached to items, RFID provides a seamless method for gathering location data, thereby enhancing efficiency, safety, and innovation [32]. The versatility of RFID technology allows it to be integrated into a wide range of applications. This paper categorizes these applications into five key areas: autonomous navigation, vehicle localization, asset tracking, product traceability, and logistics management. Each of these domains benefits uniquely from RFID localization, contributing to improved operational efficiency and enhanced service delivery [33].

RFID-enabled localization applications across several sectors are described in Fig.3. Public, manufacturing, and finance retail are the three main sectors that can be taken into consideration. Public sector examples include autonomous navigation, vehicular localization, post-operative surgery follow-up, public transit, and geo-science targets. Lastly, autonomous navigation, asset tracking, product traceability and logistic management are critical applications in the financial retail sector. It is important to note that some applications can serve across multiple sectors. Vehicle localization, which enables real-time tracking and identification of a vehicle's position in both indoor and outdoor settings, is fundamental to various subcategories such as public transportation and smart warehouses. In this section, we classify the associated applications into five main categories, focusing on RFID localization in industrial settings.

1) Autonomous Navigation

Autonomous navigation refers to the ability of systems, such as robots, drones, or vehicles, to move and orient themselves within an environment without the need for continuous human control. This capability has become increasingly essential across various industries, including logistics, manufacturing, and search-and-rescue operations. At its core, autonomous navigation relies heavily on accurate and reliable localization, knowing the precise position of the autonomous system in real time. While technologies like Global Positioning Systems (GPS) and vision-based systems are commonly used, they can be unreliable in certain environments, such as indoors, in dense urban areas, or where GPS signals are weak or unavailable. RFID technology offers a powerful alternative for enhancing navigation accuracy in these challenging scenarios.

RFID tags, strategically placed as fixed reference points, can be used by autonomous systems equipped with RFID readers to recalibrate their position and improve navigation accuracy. In industrial settings, RFID tags can store dynamic data, such as instructions or hazard warnings, along a robot's route. The robot can then read these tags and adjust their paths in real time, ensuring safe and efficient navigation. The intelligent mobile robot navigation technique demonstrates how robots could use RFID tags to navigate autonomously by reading data stored in them. [34], [35].

For outdoor environments, RFID has also been explored for long-range navigation. For example, in industrial sites or large parking lots, RFID can help autonomous vehicles navigate through wide spaces with minimal reliance on GPS. The effectiveness of RFID in enhancing long-range autonomous navigation has been demonstrated in various tests [36]. For example, in a low-cost indoor and outdoor terrestrial autonomous navigation model, RFID is shown to provide a reliable solution for navigating areas with weak or unavailable GPS signals [37]. Future advancements in RFID technology and its integration with other localization methods are expected

to further improve the accuracy and reliability of autonomous navigation across various industrial applications.

2) Vehicular Localization

Vehicular localization is the ability to determine the real-time position of a vehicle, whether it is on a road, in a parking lot, or inside a building. This technology is a cornerstone of ITS, enabling applications like autonomous driving, fleet management, traffic optimization, and enhanced road safety. Traditionally, Global Navigation Sattelite Systems (GNSS), like GPS, have been the primary method for outdoor vehicular localization. However, GNSS signals can be unreliable or even completely unavailable in certain situations, such as tunnels, dense urban areas with tall buildings, or underground parking facilities. While alternative methods exist, they often involve expensive equipment or struggle to perform well in challenging environments.

RFID technology offers a cost-effective, reliable, and precise alternative for vehicular localization, especially in scenarios where GNSS is inadequate. Ultra High Frequency (UHF) RFID tags can serve as electronic license plates or markers on vehicles. Strategically placed RFID readers, such as those on sign gantries or roadside units, can then track vehicle positions by detecting these tags. For example, RFID tags on vehicle windshields can be detected by RFID readers on overhead gantries, enabling accurate vehicle tracking. This approach is particularly useful in situations where camera-based systems might fail, such as in poor weather or when license plates are obscured [38].

RFID can also supplement GPS in areas where GPS signals are weak or unavailable. For example, RFID tags embedded in road infrastructure can provide vehicles with precise location information in tunnels or under bridges [39], [40]. This integration helps to improve localization accuracy and maintain continuous tracking, even when GPS signals are lost or degraded. RFID's ability to provide accurate positioning in environments where GNSS struggles makes it a valuable tool for enhancing safety, optimizing traffic flow, and enabling advanced applications like autonomous driving. While challenges remain in terms of standardization and widespread deployment, the ongoing development of RFID technology and its integration with other localization methods promise to further enhance the capabilities and reliability of vehicular localization systems. The future of vehicular localization likely involves a hybrid approach, leveraging the strengths of multiple technologies to ensure seamless and accurate positioning in all environments.

3) Asset Tracking

Asset tracking is the practice of monitoring the location, movement, and status of valuable physical assets in real time. These assets can range from equipment and inventory in a warehouse to vehicles in a fleet or medical devices in a hospital. It directly impacts operational efficiency, helps reduce losses due to theft or misplacement, and ultimately enhances productivity. Traditionally, asset tracking relied on manual methods or barcode systems. However, these methods are often time-consuming, labor-intensive, and prone to errors. The advent of RFID technology has revolutionized asset tracking, offering a more automated, scalable, and accurate solution.

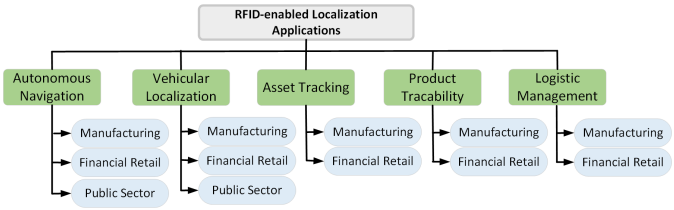


Fig. 3: RFID-enabled Localization Applications Across Different Sectors

RFID technology enables the wireless transmission of data from tags attached to assets to RFID readers, automating the tracking process and providing real-time visibility into asset locations. RFID-based RTLS are especially useful for tracking assets in indoor environments where GPS signals are unreliable. Active RFID tags, with their own power source, can transmit signals over longer distances, making them ideal for real-time tracking in large facilities such as warehouses or hospitals. Implemented RTLS using active RFID tags, can track assets with high accuracy in real-time, even in complex environments with obstructions [41]. Techniques like frequency hopping are used to avoid interference, and virtual reference tags enhance localization accuracy. Passive RFID tags, being smaller and less expensive, are often used for items that do not require constant monitoring. They are particularly well-suited for environments like retail or supply chains, where assets move through checkpoints as well as monitor inventory in warehouses, providing real-time information on item movement and location [42].

In healthcare, RFID is increasingly used to manage high-value medical equipment and consumables, reducing loss and theft while ensuring proper maintenance. Furthermore, RFID can be used to track medical instruments and devices in real-time within hospitals [43]. RFID technology has transformed asset tracking, offering a powerful tool for businesses to monitor their valuable real time with improved accuracy and efficiency. Whether using active or passive tags, RFID-based systems provide a versatile and scalable solution suitable for various industries, from healthcare to retail and logistics. The integration of RFID with technologies like IoT and cloud computing further enhances its capabilities, offering a comprehensive solution for real-time asset management.

4) Products Traceability

Product traceability is the ability to track and trace a product's journey throughout its entire lifecycle. This includes everything from the origin of raw materials to the manufacturing process, distribution, and finally, delivery to the end consumer. In today's complex global supply chains, traceability has become paramount for ensuring product safety, quality, and authenticity. It allows organizations to respond quickly and effectively to issues like product recalls, counterfeiting, and safety concerns. Industries with stringent regulatory requirements, such as food, pharmaceuticals, and luxury goods, place particular emphasis on traceability. Consumers are also increasingly demanding transparency regarding the origin and quality of the products they purchase.

RFID technology provides an efficient and scalable solution

for implementing product traceability across various industries. By attaching RFID tags to products or their packaging, companies can gain real-time visibility into their movement through the supply chain. These tags can be automatically identified and monitored at each stage of production, warehousing, and distribution. In sectors like food safety, traceability is essential for tracking ingredients and ensuring they meet health standards. RFID tags can be used to monitor the temperature and handling conditions of perishable goods, ensuring they remain safe for consumption. Similarly, in the pharmaceutical industry, RFID helps prevent the circulation of counterfeit drugs by tracking the origin and distribution of medications [44], [45]. RFID can also be used to track biological samples throughout medical processes, ensuring their traceability [45]. In the luxury goods industry, RFID tags embedded in products provide a unique identifier that is difficult to replicate, helping to combat counterfeiting. This ensures that consumers receive genuine and safe products [43].

Product traceability has become a critical component of modern supply chain management, driven by regulatory requirements, consumer demand for transparency, and the need to ensure product safety and quality. Integrating RFID with the IoT further enhances product traceability. IoT-enabled RFID systems collect additional data, such as environmental conditions or product usage, throughout the product's lifecycle. By automating data collection and providing real-time visibility, RFID enables companies to enhance efficiency, reduce errors, and improve their ability to manage risks associated with counterfeiting, recalls, and safety concerns.

5) Logistics Management

Logistics management encompasses the planning, implementation, and control of the efficient flow and storage of goods, services, and related information. It spans the entire journey from the point of origin to the point of consumption. Historically, logistics has evolved significantly. It began with basic coordination of storage and transportation, progressed to integrating production planning for optimized operations, and is now undergoing a digital transformation. This transformation is driven by the increasing adoption of advanced technologies like cloud computing, automation, and data analytics [46]. The core objective of logistics management is to ensure that the right products are in the right place, at the right time, and in the right condition, all while minimizing costs and maximizing efficiency. In today's era of digital logistics, businesses are leveraging these technologies to create more agile, responsive, and transparent supply chains [47].

RFID technology has emerged as a critical component of modern logistics management, driving digital transformation by providing real-time visibility and control over the movement of goods. RFID tags, attached to products, containers, or pallets, transmit location data as they move through the logistics chain. Readers installed in warehouses, distribution centers, and vehicles automatically scan these tags, providing up-to-date information on the location and status of goods without requiring manual intervention. In particular, the use of RFID in asset tracking has been shown to streamline operations and provide valuable real-time data for logistics management [42]. This real-time visibility allows logistics managers to monitor both vehicles and cargo continuously, enabling rapid responses to unexpected delays or route changes and enhancing the safety and security of goods in transit [48]. Furthermore, RFID's capabilities extend to challenging environments, such as metal-heavy warehouses where traditional tracking methods often struggle. RFID technology has been shown to provide accurate and reliable tracking even when signal interference is common, thus optimizing logistics management in such environments [49].

Logistics management is undergoing a significant transformation, driven by the adoption of digital technologies with RFID. As the logistics industry continues to evolve, RFID technology is expected to play an increasingly important role in creating more efficient, resilient, and responsive logistics networks.

E. Localization Measurement Techniques

In the world of positioning and tracking, localization measurement techniques are critical for determining the exact location of objects or devices. These techniques rely on the analysis of signals exchanged between devices, such as transmitters, receivers, and sensors, to calculate distances or angles, ultimately pinpointing the position of the target. In RFID localization, different models and techniques are employed to determine the position of tags based on signals transmitted between the reader and the tags. One commonly used approach is the path loss model, which predicts how the strength of a signal weakens as the distance between the tag and reader increases. This model plays a key role in estimating tag locations, as discussed by [50]. To further improve localization accuracy, researchers have explored techniques such as bearing estimation, which helps determine the direction of the signal, providing more precise location information. In addition to these advancements, studies like [51] have introduced methods to optimize RFID systems by adopting a partitioning approach, which enhances the efficiency of identifying and locating tags within a system. Innovations in RFID localization also extend to underground environments, where traditional RSSI-based methods are limited. A novel approach using antenna magnetic fields to improve passive RFID localization underground could be found such as [52] which leverages antenna magnetic fields to improve upon the limited performance of traditional RSSI-based methods.

Several widely-used localization techniques offer varying levels of accuracy and complexity, depending on the environment and application. In this section, we introduce five common methods: RSS, ToA, TDoA, AoA, and PDoA. Each technique contributes significantly to enhancing the precision of location tracking systems and is often integrated with RFID technology to develop robust and accurate solutions [5]. Fig. 4 illustrates some of the key geometric measurement methods applied to positioning a forklift truck using three RFID readers.

1) Received Signal Strength

RSS is a widely used technique for estimating the location of an object by measuring the strength of a signal as it travels from a transmitter to a receiver. The principle behind RSS

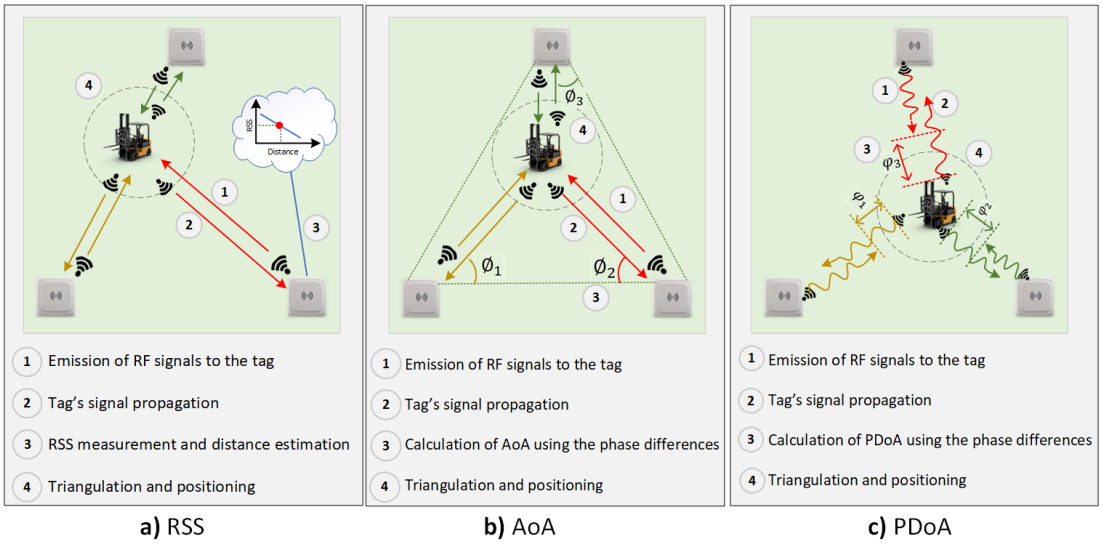


Fig. 4: Geometric-related Methods for RFID Localization

is straightforward, as a signal moves away from its source, it loses power due to path loss, which makes it possible to estimate the distance between the transmitter and receiver based on the measured signal strength.

RSS has gained popularity because it is relatively easy to implement, cost-effective, and does not require complex hardware setups. However, its accuracy can be affected by environmental factors, such as obstacles, multipath reflections, and interference. Despite these challenges, researchers have continued to refine RSS models to improve the precision of location estimates. RSS can be effectively used for real-time object localization in indoor environments. To track stationary and moving objects, making RSS a viable solution for various applications. Due to its efficiency and simplicity, RSSI-based localization has attracted a lot of interest [53].

When integrated with RFID technology, RSS provides a powerful solution for accurate and real-time localization of tagged objects. By measuring the strength of these signals at multiple points, the system can estimate the distance between the RFID tag and the readers, thereby determining the object's position [5]. The deployment of reference tags, radio maps of the pertinent environment, or a mix of these two techniques is frequently used in conventional RSSI-based locating techniques [54].

The relation between RSS and distance can be modeled using formulas that account for environmental path loss. How different environmental conditions, such as signal obstructions and clutter, can affect the accuracy of RSS-based localization, can be explored as well as the use of adaptive algorithms to improve performance is possible. One of the main challenges in using RSS for RFID localization is the variability in signal strength caused by multipath propagation, interference, and tag orientation [55]. These challenges can be addressed by combining RSS measurements with additional techniques like map matching and motion modeling to correct for inaccuracies and improve the system's performance [56]. Filtering out errors due to signal reflections or occlusions, which results in more reliable position estimates, is also possible [57].

2) Time of Arrival

ToA is a localization technique that measures the time it takes for a signal to travel from a transmitter to a receiver. By knowing the signal's speed (such as radio waves traveling at the speed of light), ToA can calculate the distance between the transmitter and receiver based on the measured travel time. This method is highly accurate and widely used in wireless communication systems, especially in environments where GPS is not reliable, such as indoors or in complex industrial settings. ToA requires precise synchronization between the transmitter (like an RFID tag) and the receiver (like an RFID reader) to ensure the accurate measurement of signal travel time. When multiple receivers are involved, the system can triangulate the signal's origin by comparing the time of arrival at each receiver, thereby determining the exact location of the object. However, environmental factors such as signal reflection (multipath interference) can affect the system's accuracy.

ToA localization can be particularly effective for tracking objects in environments like logistics and emergency response, where precision is critical [58]. Integrating ToA with RFID technology provides a robust system for accurate real-time localization. RFID tags, which transmit signals to be read by RFID readers, can be used in conjunction with ToA to determine the exact location of an object based on the time it takes for the signal to travel from the RFID tag to multiple receivers. This can be particularly useful in scenarios involving passive RFID tags, where the tag itself does not actively transmit signals but reflects the signal sent by a reader. By placing several RFID readers at known positions, the system can calculate the precise location of the RFID tag by comparing the time delays of the signal received at different readers. [58] propose a method that uses ToA to accurately localize passive RFID tags. In this method, synchronized RFID readers capture the time of arrival of signals reflected from the tag, is employed to achieve high localization accuracy.

The paper [59] discusses strategies to address multipath interference, especially in industrial settings where signal reflections are prevalent. By leveraging advanced signal processing techniques, ToA-based RFID systems can effectively reduce the impact of multipath effects and provide accurate location estimates even in complex environments.

3) Time Difference of Arrival

When integrated with RFID technology, TDoA becomes a powerful tool for achieving precise real-time localization. TDoA-based RFID systems measure the time differences of signals emitted by RFID tags as they are received by multiple RFID receivers. This allows the system to accurately triangulate the tag's location. The method is particularly effective for covering large areas and achieving precise tracking. In these systems, multiple RFID receivers are positioned at known locations in the environment. When an RFID tag emits a signal, the receivers detect it at slightly different times, depending on their distance from the tag. By measuring the time difference between the signal's arrival at each receiver, the system constructs hyperbolas to determine the tag's exact position.

TDoA provides high precision in real-time positioning systems without the need for extensive fingerprinting or synchronization between devices and reference nodes. It can achieve decimeter-level accuracy [58], [60]. TDoA-based systems can be implemented in both 2D and 3D environments, though 2D implementations are more common due to their simplicity. While this technique is effective in environments with Line-of-Sight (LoS) conditions, it can face challenges in NLoS scenarios due to signal reflections and interference.

4) Angle of Arrival and Angle of Departure

Two essential characteristics of the channel knowledge map that are frequently utilized for location-specific applications are AoD and AoA [61]. AoA is a widely used technique for determining the direction from which a signal arrives at a receiver [62]. By measuring the angle at which signals from a transmitter reach multiple antennas, AoA can estimate the location of the transmitter. Thus, this technique is commonly applied in systems with array antennas, which allow for accurate angle estimation. This method is particularly useful in environments where it is important to identify the direction of an object, such as in navigation or tracking applications.

The precision of AoA depends on factors such as the number of antennas, their placement, and the signal's frequency. While it is highly accurate in LoS conditions, it can face challenges in NLoS environments due to signal reflections and multipath effects, where the signal may bounce off walls or other objects [63]. Fig. 4 (b) illustrates how the AoA technique works. By using multiple antennas to receive signals at slightly different times or phases, it enables the system to triangulate the signal's source direction. This concept is fundamental in determining the exact location of RFID tags in both 2D and 3D spaces.

When combined with RFID technology, AoA becomes a powerful method for achieving real-time, highly accurate localization. As the use of angle measurements makes it less sensitive to noise or interference in the signal strength, RFID systems using AoA can track objects even in environments with significant multipath reflections, such as indoor warehouses or industrial sites where accuracy and real-time updates are critical [64], [63].

Unlike methods such as RSS, AoA does not require pre-collected signal strength maps (fingerprints) of the environment, this reduces the need for extensive data collection and processing, making the system easier to deploy in environments and maintenance where constant changes occur, particularly in environments where signal strength-based methods like RSS may struggle.

5) Phase Difference of Arrival

PDoA is a powerful technique used in localization by leveraging the phase differences of signals received at multiple antennas. As the signal from a transmitter, such as an RFID tag, reaches each antenna, there is a slight difference in the phase of the received signal due to the varying distances between the transmitter and each antenna. These phase differences can then be analyzed to calculate the position of the transmitter. PDoA-based localization is particularly useful in environments where other methods, such as RSS or ToA, struggle due to multipath interference or noise. In order to exploit phase difference information as a feature, one must adopt the proper antenna arrangement structure [65]. PDoA can be categorized in phase-measurement techniques, the three main PDoA-based approaches known as Time Domain (TD), Frequency Domain (FD), and Spatial Domain (SD). Unfortunately, phase-based localization suffers from phase ambiguity due to the two periodicity of phase measurements, which corresponds to the signal wavelength, making them only feasible in well-controlled environments with simple geometries and little multipath [66], [67], [10], [68], and [69].

A phase-based method can also be validated for localizing and tracking goods with UHF-RFID tags as they move along a conveyor belt. This method makes use of the known conveyor belt speed and path data and a synthetic-array methodology which it integrates concepts from knowledge-based processing, synthetic-array radar, and effective reader-tag communication signals. It is significant because it may be easily integrated into customary UHF-RFID readers without changing their antenna arrangements [70]. As another example, one proposed solution uses phase-based SAR RFID to distinguish moving tagged goods from nearby tags [71].

Several localization methods could make use of tag phase information. Based on the phase difference of signals received by nearby antennas. Time Domain PDoA (TD-PDoA) is a classical wireless location methods use triangulation using TDoA method used by GPS and the RSSI found in cell phones [66]. In Frequency Domain PDoA (FD-PDoA) the distance to a tag is estimated by measuring the tag phase across multiple frequencies, making it conceptually similar to Frequency-Modulated Continuous Wave (FMCW) radar. The method assumes that the phase offset and backscatter phase remain constant or can be calibrated out, and that the tag remains stationary during the measurements. By employing multiple reader antennas, FD-PDoA can also be extended to three-dimensional localization. There have recently been many applications of this technology to RFID in free space environments. The FD-PDoA method can be used for both

TABLE III: Measurement Techniques Evaluations

Technique	Advantages	Disadvantages	Implementation Dimension
RSS	Easy to use and economical, compatible with several integrated technologies	Depends on the antennas type, prone to ambient noise and multipath fading, might need fingerprinting, lower accuracy	2D and 3D
ToA	Highly precise localization	Time-stamp multipath effect and synchronization are problems with direct ToA, high specifications for the hardware, sensitive to Non Light of Sight (NLoS) situations	2D
TDoA	Does not need fingerprinting, precise in real-time positioning systems, does not require clock synchronization among device and RN	NLoS multipath, require clock synchronization among the RNs	2D
AoA	High localization accuracy, does not use fingerprinting, no synchronization is necessary, provide orientation information	Expensive customised hardware, multipath reflections, requires prior calibration, demands for a relatively complicated algorithm	2D and 3D
Phase-based	Can be employed to increase the localization accuracy in conjunction with RSS, ToA, and TDoA.	LoS is necessary in case of multipath propagation	2D
Fingerprinting	Easy to use	Inappropriate for challenging situations with a high number of dead zones.	2D and 3D
Proximity	Easily deployed, provide proximate position data, economical	Low accuracy and cannot state a location that is absolute, depends on the extensive use of readers or antennas, unsuitable in harsh and intricate environment, setup might be tedious (site survey)	2D

moving and stationary targets because it is similar to FMCW radar [72] , [73].

Spatial Domain PDoA (SD-PDoA) involves beam-forming techniques and spatially varied antennas to determine the location of RFID tags based on phase differences across a spatial grid. This method is commonly used in narrow-band systems, such as UHF RFID, where the goal is to determine the direction of the signal rather than the exact distance [38]. However, position ambiguity in narrow-band beam-forming systems results from an unknown number of complete wavelengths. Spatial approaches can only be used to measure the direction of the tag in narrow-band systems, like UHF RFID, and not the distance. For example, a tracking system based on RFID that uses phase measurements from numerous spatially dispersed reader antennas operating at a single frequency can be offered. By utilizing a state-space model with the location, velocity, and phase offsets as components, it is possible to eliminate the phase ambiguity biases associated with continuous wave measurements, which refer to the unknown number of full wavelengths between the object and the reader [74].

F. Lessons Learned

Although there are several important localization techniques, each with varying levels of accuracy and complexity depending on the environment and application, RSS remains one of the most popular due to its affordability, simplicity, and compatibility with a wide range of technologies. RSS is especially useful in cost-sensitive applications like industrial settings or smart environments, where adding additional hardware is not feasible. However, RSS can suffer from limitations in complex indoor environments, where signal reflections and multipath effects reduce accuracy. To address these challenges, techniques such as KFs and Machine Learning (ML) algorithms are often employed to improve precision.

On the other hand, techniques like AoA and PDoA offer higher localization accuracy, particularly in 3D spaces. These methods are favored in applications where precision is critical, such as robotics, healthcare, or autonomous vehicles. AoA, for example, excels in large-scale environments where LoS conditions can be maintained, leveraging the directionality of signals to achieve fine-grained accuracy. ToA and TDoA provide even higher accuracy but require precise synchronization between nodes, making them more suitable for environments where such coordination is feasible, like industrial automation.

In conclusion, selecting the appropriate localization technique depends on balancing accuracy, complexity, and cost. RSS-based systems are practical for affordable, general-purpose applications, while more advanced methods like AoA, TDoA, and PDoA deliver higher precision but come with increased implementation challenges. In addition, the network architecture and deployment environment, including factors such as bandwidth availability, synchronization capability, and propagation conditions, play a critical role in determining the most suitable localization technique. Understanding the specific requirements of the application, whether it requires 2D or 3D positioning, helps guide the selection of the optimal method. Evaluations of measuring techniques are listed in Tab.III, along with fingerpriting and proximity localization methods.

III. RFID Localization Methods

Localization techniques can be broadly categorized into fingerprinting and non-fingerprinting methods. This section explores a variety of fingerprinting-based techniques, such as KNN, SVM, ANN, and fusion methods. In addition to fingerprinting, it covers non-fingerprinting techniques and delves into Bayesian tracking methods, including the EM, EMM ,VBEM, BHAM, and EKF.

A. Mapping or Fingerprinting Methods

Fingerprinting methods map the position of a user, antenna, or device onto a discrete grid by utilizing online RSSI or Channel State Information (CSI) measurement techniques. Each point on this grid corresponds to a specific location in the environment where offline measurements were previously taken. As a result, fingerprinting provides a discrete location estimation rather than continuous positioning [75].

Fingerprinting typically operates in two distinct stages: the offline stage and the online stage, which set it apart from

tracking methods based on geometric measures. During the offline stage, signals such as RSS or any other position-dependent data are collected at various points throughout the environment. This data, which is referred to as a fingerprint, is stored to create a thorough characterization of the signals in the target area. When dealing with radio frequencies, the resulting database is sometimes called a radio map. The stored database serves as a reference, with each fingerprint linked to a specific location. While primarily designed for localization, fingerprinting techniques can also be adapted for tracking purposes.

For fingerprinting methods, numerous methods can be discussed from the concept of pattern recognition underpins many approaches that leverage position measurements [76] to demonstrating the robustness of kernel-based estimators which outperform used parametric maximum likelihood estimators, even under varying levels of measurement noise, when parameter values deviate from the ideal locations, ultimately achieving near-optimal location estimation performance [77]. Fingerprinting can also be combined with other techniques to enhance accuracy [78], [79].

1) Artificial Neural Networks

Artificial Neural Networks (ANN) are effective tools for enhancing localization accuracy by processing complex input data, such as RSSI values, to estimate positions more accurately. In localization, ANN learns the relationship between the signal data (like RSSI) and known positions during a training phase, allowing it to predict the position of a device when presented with new signal data in real-time. The model is especially valuable in scenarios where the signal data is nonlinear or affected by noise, as ANN can learn these complexities and compensate for them during position estimation. ANN is often combined with other techniques like k-means clustering or data fusion strategies to enhance the robustness of the localization process. An ANN-based multi-sensor positioning system can integrates RFID technology and enhances localization accuracy by fusing it with Computer Vision (CV) data as well [80]. ANN can be used to train the system using RSSI values and their associated coordinates during the offline phase, enabling it to estimate user positions in the online phase with new RSSI data [81].

2) Support Vector Machine

One of the most widely used ML algorithms is SVM, which can function as both a classifier and a regressor. SVMs handle both linear and nonlinear data by mapping the input features onto an n-dimensional feature space. In this space, a hyperplane is used to classify the data into distinct categories while maximizing the margin between the classes. The transformation of the data into a higher-dimensional space is achieved through kernel functions, and the choice of the kernel significantly influences the accuracy of the SVM model. SVM can be applied to localization using both offline and real-time RSSI measurements. Some easy-to-use SVM-based localization methods for strategically placing RFID tags can be possible, in one approach ([82]) synthesized sensor data are generated from a limited set of real sensor data to provide diverse training data for SVM learning.

Another notable application of SVM is in Support Vector Regression (SVR), where it is used to analyze phase difference data from multiple RFID receivers. In the event of accuracy, an interesting work ([83]), the authors tested the performance of SVM regression using six datasets with varying sizes and locations within the area covered by the RFID receivers. Additionally, two training sets based on different grid sizes were considered for the regression. While an overall accuracy of less than one millimeter was not achieved in the experiments, the deviation was typically within two millimeters. Moreover, as an example of the approach which brings several positive benefits, particularly in improving model robustness and generalization, maximizing the margin in SVM is equivalent to minimizing the worst-case loss, rather than some average quantity like Mean Squared Error (MSE) [84]. Some of findings suggest that RFID localization could soon be applied in highly sensitive fields, such as brain surgery.

3) k-Nearest Neighbor

KNN is a supervised learning technique that is widely used for both classification and regression tasks. It falls under the category of range-free fingerprinting methods. The core principle of KNN is to categorize input data based on how close the features in the training set are to those in the testing set. The number of neighbors considered by the algorithm is often influenced by the amount of noise in the data. When working with a low-dimensional feature space, KNN requires less training data, making it an efficient method for many localization tasks.

In situations where GPS-based positioning is unreliable, such as indoors, location fingerprinting becomes a useful technique. However, maintaining user privacy has become a significant challenge in location estimation systems, as location service providers typically have access to sensitive location information [85]. KNN uses the Root Mean Square Error (RMSE) to calculate the k-nearest matches for a given location based on offline RSSI measurements stored in a database [86]. If the distances between the signals are used as weights, it is referred to as weighted KNN; otherwise, it is known as non-weighted KNN [75].

In a system which employs a combination of KNN, RSSI, and reference tags for location sensing within buildings, active RFID is a cost-effective and suitable technology for indoor localization, despite RFID not being originally intended for such use [87]. The effectiveness of RFID technology in improving location accuracy can be explored. When combined with technologies like WiFi, GPS, and Zigbee, RFID's identification capabilities to enhance the performance of localization techniques [88].

Fig. 5 presents a comparison between three ML techniques, ANN, SVM, and KNN (with $k = 5$) applied to localization tasks based on randomly generated RSSI data. It effectively illustrates how each technique processes and classifies RSSI data for localization, with varying levels of precision and computational cost. The RSSI signals represent the strength of radio waves received by an RFID reader from a tag, and they are typically measured in dBm (decibel-milliwatts). RSSI values can typically range from around -40 dBm (strong signal) to -80 dBm (weak signal) in industrial settings, depending on factors such as distance between the tag and

the reader, obstacles, and signal interference. The main goal of these graphs is to show how well each method, ANN, SVM, and KNN, classifies positions or "classes" based on RSSI data, which simulate various locations within an indoor environment. A "class" refers to a distinct location within the space, and the task for each algorithm is to predict the correct location (class) for new RSSI data points. Each technique uses a different approach to process the data and make accurate predictions about the tag's location.

In the case of KNN, the algorithm classifies a new RSSI signal by comparing it to the closest examples in the training set. It identifies the KNN based on signal strength similarity and predicts the location based on the most frequent class among those neighbors. SVM, on the other hand, seeks to find an optimal boundary between the different classes of RSSI data, making it especially useful for non-linear classification problems. ANN, with its layered structure of interconnected neurons, processes the RSSI signals by applying weights and activation functions to learn complex patterns in the data. ANN is particularly effective in environments where RSSI data fluctuates due to interference or non-linearities, enabling more precise location prediction.

B. Non-fingerprinting Methods: An Emphasis on Proximity

Non-fingerprinting methods estimate a device's location using real-time measurements and geometric principles rather than signal fingerprints. Proximity-based localization is one of the simplest non-fingerprinting techniques. Proximity can be classified as a range-free method, meaning it does not require precise signal measurements. It works by determining the device's position based on its proximity to known reference points, such as RFID readers or Wi-Fi access points. For example, when a device is detected by an RFID reader, its location is assumed to be near that reader, with signal strength indicating how close the device is. While proximity-based localization is advantageous due to its simplicity and low cost, and easy to deploy because it does not require complex hardware or time synchronization between devices, it does have limitations. The accuracy of proximity is generally lower than other methods, and it is heavily dependent on the deployment of readers or antennas. Proximity is not suitable for harsh or complex environments and cannot provide absolute positioning. Its reliance on the extensive use of infrastructure, such as readers or antennas, further limits its effectiveness in certain scenarios [5], [89], [90], [91].

It simply uses binary connectivity to infer the position of devices, making it ideal for quick and general location estimates, especially in areas where precise tracking is not essential. Another group of non-fingerprinting techniques includes hop counting, which estimates distance based on the number of network segments, or "hops," a data packet passes through as it moves from one node to another. Each hop provides a clue about the relative distance between the nodes. In more complex approaches, the positions of nodes can also be inferred using graph embedding techniques, where the relationships between nodes are represented in a graph, and the structure of the graph is used to estimate the locations of the nodes [92], [93].

C. Hybrid Fusion of Multiple/Different Sensors

Hybrid sensor fusion combines data from both proprioceptive sensors, such as IMU and encoders, and exteroceptive sensors, such as laser range finders, sonars, and cameras, which capture environmental data. The integration of these different types of sensors helps enhance the accuracy and reliability of localization systems. By blending proprioceptive and exteroceptive data, sensor fusion prevents drift in estimated trajectories and bounds localization uncertainty, ensuring more stable positioning over time [12], [94], [95] [96].

As a hybrid fusion clear example of using microelectromechanical systems, a low-cost localization system can be designed for challenging environments, combining microelectromechanical system inertial sensors with wireless Time-of-Flight (ToF) ranging. This hybrid system can be achieved a sub-meter precision with a much lower update rate than the standalone wireless Ad-hoc system for positioning. By fusing data from multiple sensors, the system improves scalability and availability while also reducing power consumption [97].

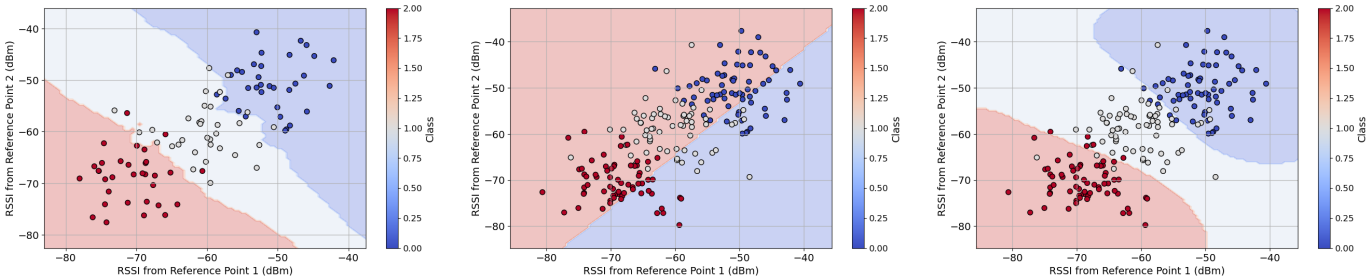
The sensor fusion methods for tracking human movement can be purposed by integrating data from multiple sensors. One of the key challenges of inertial data is that position estimates tend to degrade over time due to measurement uncertainty. To address this, a heuristic approach can be used to keep velocity estimation uncertainty within a few percent, resulting in improved localization accuracy, especially when the wearable platform is worn around the waist. Additionally, the low-rate position data collected from an external fixed infrastructure can be fed into an EKF to prevent the unbounded expansion of uncertainty [98].

The potential of fused tracking methods is particularly evident in environments where traditional wireless or sensor-based tracking systems might fail, such as low-light, smoke-filled, or power-limited. Furthermore, head-mounted displays provide real-time navigation directions directly into the user's LoS. The system requires minimal setup and calibration, as it can be configured simply by walking through the environment and annotating a 2D map [99].

D. Bayesian Tracking Method

Bayesian tracking methods have become a cornerstone in wireless tracking systems, which typically involve fixed reference nodes (also known as anchor nodes or landmarks) and mobile nodes (such as agents, targets, or mobile users). In the context of RFID localization fingerprint-based, non-fingerprint-based, and hybrid approaches describe how localization information is obtained and processed at a system level. In contrast, Bayesian tracking methods (e.g., KF, Particle Filter) represent a class of estimation techniques used to refine or track position over time, rather than a standalone localization paradigm. Therefore, they can be treated as a separate class to highlight their complementary role across different localization paradigms.

Bayesian tracking algorithms are probabilistic methods used for estimating the position of moving objects based on prior knowledge and current observations. These systems track moving objects by measuring the relationships between these



(a) KNN classification for RSSI data (b) ANN classification for RSSI data (c) SVM classification for RSSI data

Fig. 5: Fingerprinting Methods.

nodes. It means continuously updating the estimated position of an object by combining a prior belief about its location (often based on a motion model) with new data collected from sensors (such as distance measurements between nodes). For instance, in cellular-based tracking systems, mobile nodes are often referred to as user equipment, while anchor nodes are known as mobile stations. In some advanced applications, such as SLAM, both mobile and anchor nodes are localized simultaneously as they navigate a predefined path [5].

The Bayesian tracking process typically involves two steps: prediction (the motion model) and update (the observation model). In the prediction step, the object's future state is estimated based on the current state and a motion model. This predicts the user's next position based on physical movement constraints such as velocity and acceleration. This is inherently a non-fingerprinting approach because it relies on physics and kinematics rather than stored signal data. Then, in the update step, this prediction is corrected based on the new sensor measurements, improving the accuracy of the object's estimated location. The observation model can be inherently a fingerprinting or non-fingerprinting approach. If the observation model uses signal propagation models such as RSSI, the tracking is non-fingerprinting-based. If the observation model uses radio maps, the tracking is fingerprinting-based. Bayesian tracking is highly versatile and can handle uncertainty in the system by continuously refining its estimations, making it suitable for real-time tracking in dynamic environments. It is possible to investigate the use of Bayesian inference techniques in conjunction with random sampling algorithms in wireless tracking systems, which are reaching remarkable localization accuracy. The system's dependence on movement probabilistic models, which may compromise accuracy if the model does not correspond with actual movement patterns, may be one of the main drawbacks [100], [101]. It is important to consider, as the exact positions of the mobile nodes are typically unknown and need to be estimated, whereas the anchor nodes' locations are known, thus the process involves taking precise, position-dependent measurements between nodes, such as the distance between them, and using this data to estimate the location of the mobile nodes [102].

To fully understand the potential and limitations of RFID localization based on Bayesian principles, and wireless tracking systems in general, it is essential to evaluate the various approaches used. Each method has its own advantages, but they also present challenges, such as the reliance on probabilistic models or the accuracy of the measurement data.

1) Exact Method

The EM is a localization technique that aims to determine the precise[2] spatial coordinates of mobile nodes within a wireless tracking system. Unlike probabilistic approaches, the EM is based on deterministic computations, which use known measurements, reference points, and mathematical models to calculate the exact position of a target. This method by utilizing information such as signal strength, ToA, or phase measurements, can determine the exact location of mobile nodes within the environment, it means the method leverages advanced geometric algorithms and mathematical paradigms to achieve high accuracy, making it a preferred approach in applications where precision is paramount and particularly useful in static environments, where the positions of reference nodes are known and constant.

However, despite its theoretical precision, the EM often encounters challenges when applied in real-time, dynamic environments. The high computational complexity of the method can limit its practicality in fast-moving or large-scale deployments. Calculating exact positions in real time requires significant processing power, which can introduce delays and affect system performance. Therefore, while the EM excels in accuracy, it may require optimization or alternative approaches to handle the computational demands of real-time systems effectively [103].

2) Expectation Maximization Method

Expectation Maximization is a statistical method used to estimate unknown variables in a dataset, even when some information is missing or uncertain. It works by alternating between two steps: first, it guesses the missing or hidden data (this is called the expectation step), and then it updates the model based on these guesses to find the best possible solution (the maximization step). This process repeats until the estimates get as accurate as possible. EMM is especially useful in situations where we have incomplete data or when we need to improve an estimate over time, such as in localization tasks where the position of an object is uncertain. EMM excels iteratively can be improved the accuracy of position estimates through the maximization of a probability function, taking into account both observed data and latent factors, unobserved variables that can affect the outcome [103].

[2]However, they are still subject to errors as they are based on measurements.

3) Variational Bayesian EM Method

The VBEM is an advanced technique that builds on the EMM. It uses Bayesian inference to handle complex models and large datasets while managing uncertainty in the data. In VBEM, instead of directly solving for the most likely position or outcome, the method approximates the probability distributions of possible outcomes, which helps provide more accurate and reliable results, partcularly VBEM is useful when dealing with uncertainties in systems, such as the positions of anchor nodes and mobile nodes in RFID localization. It means that Bayesian principles are applied to not only estimate positions but also to account for the uncertainties that come with the measurements. VBEM adjusts and refines these estimates over time, leading to a more accurate and reliable localization solution. [103].

4) Bayesian Hierarchical Appearance Model

BHAM is a method that combines Bayesian theory with a system's visual or sensor-based characteristics to improve object tracking and localization. Instead of relying only on the physical position of nodes (like distance or coordinates), BHAM also takes into account what the nodes "look like" or how they appear in terms of sensor data. This extra layer of information helps to better distinguish and identify objects, leading to more accurate and reliable localization. BHAM works by creating a hierarchical model where data from different levels, such as distance measurements and visual or sensor data, are integrated and processed together. This combination makes BHAM particularly useful in environments with many visual or distinguishing features, where basic distance measurements alone may not be enough. BHAM is particularly effective when applied to wireless tracking systems, as it goes beyond just measuring distances andit improves the accuracy and reliability of localization, especially in environments where there are plenty of visual cues or distinguishing features [104].

5) Kalman Filter and Extended Kalman Filter

KF is a widely used algorithm for state estimation in systems with linear dynamics. It works by continuously refining predictions of a system's current state, such as position or velocity, based on a combination of prior estimates and incoming measurements. The filter operates recursively, which means it updates its estimates as new data becomes available, making it highly efficient for real-time tracking. The KF assumes that both the system dynamics and noise affecting measurements are linear and Gaussian, which makes it ideal for environments where these assumptions hold true.

For non-linear systems, where the assumptions of linearity do not apply, the EKF is used. The EKF works similarly to the KF but introduces an additional step: it approximates the non-linear system by linearizing it around the current estimate. This allows the EKF to handle more complex tracking problems, such as those found in environments with irregular motion patterns or varying dynamics, by transforming the non-linear system into a form that the KF can process effectively [105].

In applications such as wireless tracking systems, the KF is a widely used recursive Bayesian filtering technique for state estimation and tracking. This method maintains a Gaussian probability distribution across state variables, allowing for both computational efficiency and accuracy in environments characterized by linear system dynamics and Gaussian noise. Essentially, the KF functions as a recursive mathematical tool that continuously refines its predictions by combining new measurements with prior estimates, ensuring precise updates to the current state of the system. It is particularly well-suited for real-time applications, as it efficiently updates the position of mobile nodes in RFID localization systems, even when using complex motion models [106].

An advanced example of this approach is the hybrid cooperative EKF, which is specifically designed to provide more accurate estimates of mobile device positions. The hybrid cooperative EKF algorithm considers a wide range of observations, such as RSSI measurements between WSN nodes and UHF-RFID tag detection events. This method consists of three key components: state modeling, hybridization, and cooperation, all of which work together to refine the tracking process [107]. For instance, in [108] examines the impact of multipath propagation and non-isotropic radiation from tag antennas on RSSI measurements and overall tracking performance. The authors account for these effects by calculating the maximum likelihood estimate of the RFID reader's position in a 2D Cartesian space. The KF is then applied to dynamically predict the reader's trajectory, based on these estimates of position and velocity.

TABLE IV: Qualitative comparison of the computational demand and deployment complexity of RFID localization methods.

Method	**Comp.**	**Deployment Complexity**
Fingerprinting	Medium	High (offline radio map required)
Non-fingerprinting	Low–Medium	Low
Hybrid fusion	Medium–High	High (multi-sensor integration)
Bayesian tracking	High	Medium–High (model configuration and parameter tuning)

E. Lessons Learned

In summary, methods like KFs, EM, VBEM, and BHAM are widely used in RFID localization and wireless tracking systems. The choice of method depends on various factors, including the required precision, computational resources, and the specific characteristics of the tracking environment. Each method has its own advantages and limitations, requiring careful consideration according to the application requirements.

Fingerprinting methods, such as KNN, SVM, and ANN, are particularly suitable for applications requiring high localization accuracy, including smart warehouses and asset tracking systems. By constructing an offline radio map, these methods can achieve *cm*-level localization accuracy in relatively static indoor environments. However, their scalability is limited because maintaining the fingerprint database becomes increasingly labour-intensive as the environment changes. In contrast, non-fingerprinting methods are better suited to dynamic and large-scale environments because they eliminate the need for offline calibration and radio map construction. These methods provide greater deployment flexibility and lower computational requirements, although they generally achieve lower

localization accuracy in environments affected by multipath propagation and signal interference. Hybrid fusion approaches combine RFID with complementary technologies, such as WSNs, SLAM, SAR, IMUs, LiDAR, or cameras, to significantly improve localization robustness and accuracy, making them particularly attractive for demanding applications such as industrial automation and autonomous navigation.

The four localization methods can be characterized by different trade-offs, mainly in terms of localization accuracy, computational complexity, hardware requirements, deployment effort, and robustness under different network settings. Fingerprinting methods generally provide high robustness against multipath and NLoS conditions, making them suitable for complex indoor environments; however, they require extensive offline training and radio map construction. Non-fingerprinting methods eliminate the calibration stage and offer lower deployment effort, reduced computational complexity, and faster update rates, although their performance is more susceptible to environmental variations and signal propagation effects. Hybrid fusion approaches achieve the highest localization accuracy and robustness by combining RFID measurements with complementary sensors, such as IMUs, cameras, or LiDAR, but this comes at the expense of increased hardware complexity and system cost. Bayesian tracking methods provide reliable localization in dynamic environments by incorporating probabilistic motion and measurement models, offering a balance between localization accuracy, computational complexity, and hardware overhead while maintaining continuous tracking capability.

Although the computational complexity varies depending on the specific algorithm and implementation, the surveyed methods exhibit several general trends. Non-fingerprinting methods generally exhibit the lowest complexity because localization is performed using direct geometric or signal-based estimation without requiring an offline training stage. Fingerprinting methods incur additional deployment complexity through radio map construction, while hybrid sensor fusion increases computational requirements through multi-sensor data integration. Bayesian tracking methods generally present the highest computational complexity because they continuously estimate system states using probabilistic inference over time. Tab. IV provides a qualitative comparison of the computational demand and deployment complexity of the surveyed localization methods. The comparison is qualitative and reflects general trends observed across the surveyed studies and may vary depending on the specific algorithm and implementation.

IV. Comparative Analysis of RFID Localization Studies

In section IV-A, we review industrial RFID localization research papers, first categorizing them into two broad groups: those focused solely on RFID and those integrating RFID with other technologies such as WSN, SLAM, SAR, and other emerging technologies. This classification reflects the growing industrial need for hybrid systems that leverage multiple technologies for improved localization accuracy and robustness. The inclusion and exclusion criteria for the reviewed works are detailed in Section I-B2.

In section IV-B, we proceed with a statistical evaluation of the surveyed papers, identifying trends in research focus, commonly used algorithms, and the evolution of RFID localization technologies. This analysis helps to highlight the gaps in the current landscape, revealing opportunities for future advancements. Finally, in section IV-C, we present the key lessons learned from the comprehensive survey. The structure of this section is illustrated in Fig. 6.

A. Literature Review and Learned Lessons

1) Solely RFID with/without Odometry Sensors

This subsection reviews research papers that focus exclusively on using RFID technology for industrial localization purposes. After summarizing the key papers, we conclude with the lessons learned from these works.

A. Surveyed Papers Several papers have studied RFID technology, with or without odometry sensors, for industrial localization, such as [69], [33], [109], [30]. The study in [69] proposes a localization solution for an indoor autonomous vehicle equipped with an RFID reader and odometry sensors. The system scans tags placed on the ceiling to localize the mobile robot without any prior knowledge of its initial position. The RFID reader measures signals from the tags based on phase, which is influenced by the robot's distance from the tags, though the phase is also highly sensitive to small positional changes within the frequency range used. To address this sensitivity, the authors employ a particle EKF, a multi-hypothesis KF technique that performs well. The study highlights how the proposed methodology performs in noisy environments, with both simulated and real-world results. For a novel approach employing an iterative multi-hypothesis KF, the reader is referred to [33]. This method mitigates linearization issues in nonlinear systems and addresses position uncertainties arising from the 360-degree phase ambiguity of RFID signals. In [110], the apparatus has an optical camera and a UHF RFID reader. Using a KF to combine the corresponding optical and RF readings, these landmarks are used to estimate the handheld reader's attitude over time. By combining the estimated antenna trajectory with the unwrapped phase data, the positions of the tags are estimated. By recognizing the attached tag, the system in [111] locates the item and uses the RF interference of coupled tags to help localize the target. The authors created a prototype of the system and conducted in-depth testing to assess its performance. This method successfully achieves highly refined localization accuracy with less than 1 cm errors.

[109] provides a detailed comparison of computational time and accuracy. In [109], the authors provided a Trajectory-robust Relative localization algorithm to order tags according to the connection between phase profiles and tag-to-tag distance. By progressively determining each tag's position interval in the tag sequence, one can achieve relative localization of all tags by using the dynamic time warping algorithm to compute correlations between the phase profiles of various tags. It is suggested to use a virtual-actual assembly

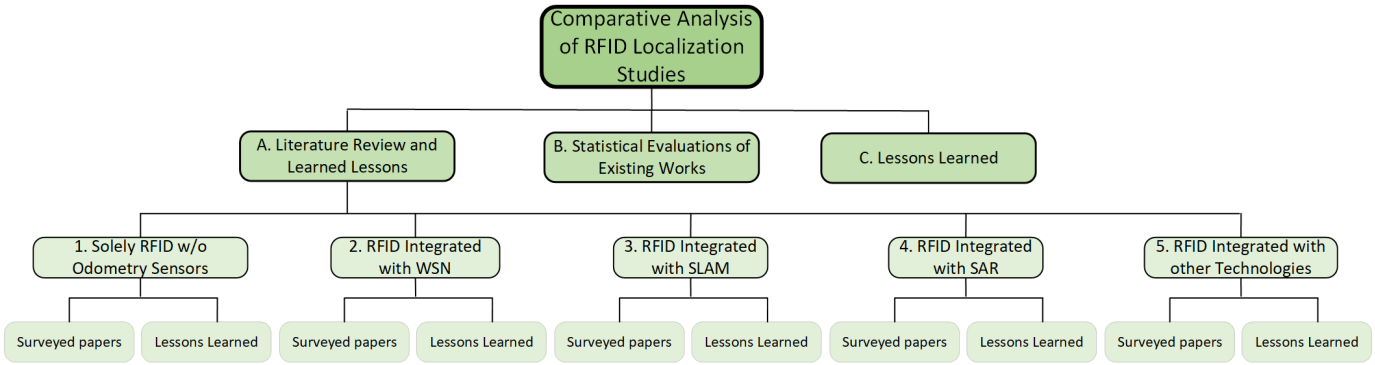


Fig. 6: Organization of the comparative analysis of RFID localization studies

approach to accomplish cooperative and distributed localization. In [30], an anti-multipath algorithm based on differential analysis introduces a proposed reference tag. The virtual actual assembling, which is the core of this method, has remarkable convergence and error-equality properties that make it easier to practically design the virtual phase's pass number and the real phase's assembly sequence. Additionally, the suggested approach performs better than the other algorithms with desirable stability, according to the coarse-grained evaluation.

Device-free localization enables indoor placement without requiring the target to carry any radio equipment, making it highly versatile for various applications. Unlike previous works [112] improves upon traditional methods by using preliminary fuzzy localization derived from radio tomographic imaging results. RFID-based radio tomographic imaging has gained attention for its ease of deployment, real-time performance, and low cost. However, the accuracy of this method is heavily influenced by how well the model adapts to the environment. By assigning appropriate weights, their method achieves device-free multitarget localization and outperforms traditional radio tomographic imaging, particularly in crowded indoor environments. To address large-scale tag localization with frequent missing measurements, MUSE, a multistage assembling approach, is proposed in [113]. The core of MUSE lies in selecting the appropriate fragment map. This helps correct fragment maps and prevents errors from propagating to later stages. Among five evaluated strategies, selecting the fragment map with the largest number of vertices proved the most effective.

For the development of a tag localization system using standard RFID hardware, [114] presents a compelling solution through the SparseTag approach. The SparseTag system is built on four key components: a direction of arrival estimation method, a difference co-array design, spatial smoothing for direction of arrival estimation, and sparse array processing.
In [115] a reference-free RSS-profile method is introduced for localizing tagged items inside closed drawers. To determine the relative and absolute positions of each tag, an RSS profile is created, and its features are used for positioning. Initially, the X-axis coordinate is roughly estimated by analyzing the peak asymmetry factor. The absolute position is calculated by correcting the X-axis bias and applying an RSS-base ranging model to estimate the Y-axis coordinates of the tags in the same column. Extensive experimental results show that this approach provides high accuracy for both relative and absolute localization within closed drawers, confirming the robustness and effectiveness of the method. In [116], the fusion of numerous measurements enhances the estimation performance as more iterations are finished as well. This paper's primary components are an IMU, which measures rotation angles, and a UHF RFID reader that runs on a single antenna.

In [117], the authors take advantage of the polarization effect to produce polarized phases, which eliminates the effects of tag angle. The system obtains pure phases, that is, the phase corresponding to the path of sight by using polarized phase decomposition. Phase unwrapping and phase filtering based on the discrete wavelet transform improve phase accuracy, and a phase model based on the polarization effect is proposed to compensate for the phase error caused by ignoring the label angle in the existing phase model. To increase the dimensionality of the data and the signal strength and phase difference of the RFID tag as feature inputs, [65] proposes an indoor localization algorithm based on back propagation SVR, which uses the hidden layer of the Neural Network (NN). In this work, the rate of model learning is accelerated through the application of the sequential minimal optimization algorithm.

On the other hand, the authors of [17] created a greedy algorithm that employs a novel score function to help deploy the RFID tags in a given area to ensure maximum coverage in order to optimize the coverage utilizing a limited number of tags. Low-density reference tags inside a restricted space can achieve satisfactory tracking capabilities, as demonstrated by the preliminary experimental findings using an RFID robot in a real indoor environment in [18].

B. Lessons Learned Compared to many other integrated technologies, adopting an RFID-only design, with or without odometry sensor data, is one of the most efficient ways to create a hybrid industrial localization system. This system combines RFID localization based on widely used and cost-effective passive UHF RFID technology, which offers *cm*-meter-level accuracy with the sensor's odometry data. This also allows persistent high-precision localization without the need for costly extroceptive sensors, such as camera, sonar, or laser technology and lowers the RMSE to a few *cm*-meter-level in the open plan office [33]. This type of system can

be tested more easily than many other integrated wireless technologies with RFID in real industrial environments. For instance, the robot's distance from the tags can be estimated, while phase measurements, being highly sensitive to small positional changes within the operating frequency range, can be effectively exploited using methods such as a particle EKF, even in areas with sparse tag density [69]. The findings reveal that such a system and its approach can maintain low computational complexity while providing high localization accuracy and stability in various indoor environments. Evaluating the accuracy and real-time performance of RFID-based localization algorithms requires a realistic simulation environment tailored to industrial settings. To model these conditions, one replicates the room geometry and the precise antenna/tag configurations of the experimental testbed. These synthetic values are subsequently perturbed to account for the primary sources of measurement discrepancy: receiver-induced white phase noise and multipath propagation effects, which is fully described in some of the works such as [33]. Moreover, such a system can be applied and designed simply to a wide range of moving agents, including autonomous ground vehicles, aerial vehicles, drones, and robots, operating both indoors and outdoors. As an example, Trajectory-robust Relative clearly has a benefit in terms of system deployment because it does not require the reader to move in a strictly straight line or extra devices in order to get the reader's trajectory coordinates. The system can test its effectiveness with vehicles moving at higher speeds across more complex and large-scale landscapes, all while requiring a low-density deployment of reference tags. The primary limitations of phase-based UHF-RFID, periodicity-induced ambiguity and unpredictable, configuration-dependent phase offsets, are typically mitigated through signal unwrapping and the adoption of the PDoA approach, respectively. To optimize vehicle tracking in expansive settings, RFID observations are combined with proprioceptive sensor data (e.g., IMUs, encoders) via sensor-fusion architectures. These systems rely predominantly on sequential estimators such as the EKF, UKF, or PF, with occasional applications of smoothing or FIR filtering to handle dynamic state estimation [18]. This approach presents a promising solution for tracking and localization in a variety of industries, offering a scalable and efficient method for vertical industries and businesses.

2) RFID Integrated with WSN

This subsection offers an evaluation of the research papers on RFID localization integrated with WSN. After reviewing the papers, we present the lessons we have learned.

A. Surveyed Papers In [107], a hybrid positioning system integrating RFID and WSN technologies is developed to improve indoor localization accuracy in IoT environments. Using a hybrid cooperative EKF, the system processes both RFID tag detection events and RSSI measurements from WSN nodes. The combination of these technologies enhances positioning robustness, with MC simulations showing improved tracking performance and reduced RMSE compared to using WSN alone. The study demonstrates that hybrid solutions offer better accuracy and reliability in challenging environments, addressing RSSI noise issues through an optimization technique and showing the value of integrating RFID with WSN for real-time tracking. Two other similar hybrid positioning strategies based on WSN and RFID are presented in [118] and [119]. In [119], the hybrid cooperative EKF algorithm extends the conventional EKF by incorporating hybrid and cooperative features, including state modelling, hybridization, and cooperation mechanisms.

B. Lessons Learned WSN with UHF RFID technology provides good coverage and reliability. Its main drawback is its low accuracy solution; its main advantage is its low power consumption. Since WSN typically offers *cm*-meter-to-meter accuracy for RFID localization and positioning, it is most suitable to avoid selecting WSN for localization targets if accuracy is the most crucial performance metric in design. A wireless sensor node is a common solution when it is difficult or impossible to supply a mains supply to the sensor node. WSN is carried out using PDoA and RSS, with a range of one to ten meters and a median accuracy of less than 5 meters. MATLAB can be used as a simulation tool to evaluate these hybrid approaches, demonstrating that WSN/RFID integration is feasible and can provide accurate positioning even in challenging indoor environments [118], [107]. In RFID-WSN integrated systems, position estimates and associated uncertainties from mobile nodes can be incorporated into a hybrid cooperative EKF algorithm. Results show that the hybrid KF-based approach outperforms non-cooperative methods. The EKF can be evaluated under different configurations, including hybrid cooperative EKF, cooperative EKF based solely on WSN, hybrid EKF without cooperation, and a baseline EKF based solely on WSN without cooperation. In general, long-distance wireless communication can be costly in terms of energy consumption and implementation difficulty. Energy minimization can also be taken into account while constructing the physical layer of sensor networks, in addition to the impacts of decay, scattering, shadowing, reflection, diffraction, multipath, and fading [120]. In experimental evaluations, to address tracking challenges caused by high packet loss and missing RSSI signals, the inclusion of RFID observations is essential [107]. This hybrid approach improves overall system availability and meets the rigorous demands of industrial-scale deployments.

3) RFID Integrated with SLAM

This subsection provides the evaluation of research articles on RFID localization integrated with SLAM. We summarize the lessons we have learned after reviewing all the articles.

A. Surveyed Papers In [121], the authors use a SLAM technique, where a mobile robot with a reader antenna locates the tags positioned inside an indoor environment, and present a dependable 2D localization technology that is competitively accurate and faster than state-of-the-art methods. The effects of antenna height as well as antenna trajectory distance and length were also taken into consideration. Phase measurement-related issues are a major drawback to the suggested method's effective use. For the simultaneous 3D estimation of the robot's

TABLE V: Proposed Systems in the Literature

Research	Year	RFID Application	Integrated Technologies							Measurement Techniques			Performance Metrics					
			WSN	LiDAR	SLAM	SAR	Cellular	Laser	Wearable	RSS	Phase	Other	Accuracy	Coverage	Reliability	Robustness	Cost	Speed
[107]	2013	Indoor Positioning, General-purpose IoT Environment	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗
[119]	2011	Indoor Positioning	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓	✗
[118]	2011	Indoor Positioning	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
[69]	2014	Global Localization Problem Considered, Mobile Robot	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗
[32]	2022	Robot, Indoor Positioning	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗
[33]	2022	Robot Localization, Indoor	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
[109]	2023	RFID Mobile Localization	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗
[121]	2022	Indoor Mobile Robot Positioning and Tracking, Multiple-tag Scenario	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓
[12]	2022	Tagged-item Inventory and Localization	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[30]	2023	Indoor	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[112]	2022	Device Free Localization and Wide Range of Applications in Indoor Placement	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓	✗
[113]	2022	Large-scale Massive Passive RFID Simultaneous Localization	✗	✗	✗	✗	✗	✗	✗	✗	✗	-	✓	✗	✓	✗	✓	✓
[115]	2022	In Closed Drawers	✗	✗	✗	✗	✗	✗		✓	✗	✗	✓	✗	✗	✓	✗	✗
[114]	2022	Indoor Backscatter Localization	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗
[122]	2023	Robot Positioning, Smart Warehouse Positioning	✗	✓	✓	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓
[123]	2022	Indoor, Robot Positioning	✗	✗	✓	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✓	✗	✗
[110]	2023	Real-time 3D Localization of Products	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓		✗	✗	✓	✗
[116]	2022	Indoor	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[31]	2023	Indoor Positioning, Mobile Unit Equipped by Wheel Encoders and RFID Reader	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[65]	2022	Indoor Localization Algorithm	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗
[18]	2021	Indoor Vehicle Tracking with Low-density UHF-RFID Tags	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓
[17]	2019	Indoor Localization System for Moving Targets	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗
[124]	2019	Robot Trajectory	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓
[125]	2015	Indoor Localization	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
[126]	2018	Robot Localization	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗
[117]	2022	3D Localization	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
[127]	2021	Tracking Visitors' Movement within a Museum	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✓	✗
[15]	2020	3D Indoor Localization	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✓
[128]	2011	Indoor	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[70]	2015	Locate Items	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
[111]	2018	Many Applications Such as Autonomous Robots	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗

and the tags' positions in a warehouse environment with just a cost RFID device and no additional sensors or reference tags, see [122]. The front-end and back-end algorithms make up the technique. The authors estimate the robot's trajectory and the relative locations of the tags in the RF-SLAM front end. The front end is suggested to be a multiantenna-based relative localization technique that quickly uses odometer data and phase monitoring.

[123] addresses a SLAM problem in which the robot's localization depends on the estimation of the tag positions to produce a reference map. The usage of a unique type of tag, the tri-lateration tag, with three antennae adjacent to one another, is one of the novelties of the paper. A set of multi-hypothesis EKF, one for each tri-lateration tag, is used to estimate the range and bearing of every tri-lateration tag that has been detected. In [31] The authors examine how this dependence affects the SLAM problem by contrasting the methods where this dependence is compensated through a time-varying phase offset that is subject to estimation with the method where it is included in the measurement model. Results from experiments and simulations demonstrate that, in comparison to the other method, the algorithm that incorporates this dependence in the measurement model yields better performances. In [124], the approach is meant to automatically compensate for the offsets' influence by appropriately adjusting the estimate of tag height, as demonstrated in the paper, hence eliminating the need for offset estimates. To address the issue, a Rao-Blackwellized PF is used. The efficiency of the suggested

method, which enables the estimation of the robot trajectory and the tag coordinates with an accuracy in the order of one *cm*-meter in simulation and of a few *cm* under real data, has been demonstrated through the reporting of both simulation and experimental findings.

B. Lessons Learned In general, accuracy in SLAM is achievable possibly at the *cm-mm* level, and enables us to simultaneously create a map and localize our antenna, robot, and vehicle on it. SLAM can be achieved by several means such as wheel encoders' odometric data, sonars, or laser scanners. Costliness and the need for LoS conditions are the primary drawbacks. Two primary challenges with SLAM technology are as follows: The first is mapping, which involves determining 3D location of RFID-tagged objects. Another is localization, which involves figuring out where the mobile target such as drone, vehicle, or robot is. In the SLAM approach, longer motion mobile paths have been shown in some works to allow for more precise tag location estimates. Through many motion repetitions, the movable robot, vehicle, or antenna in SLAM is able to reacquire some measurements and reject incorrect readings in favor of higher-quality ones. Note that in the single-tag example, reconstruction errors in the antenna, robot, or vehicle motion may affect the tag localization accuracy. *cm*-level accuracy can be achieved with SLAM-based approaches through various methods, such as employing graph-based models that account for robot odometry constraints and RFID tag observations. The choice of approach often depends on the application scenario; for instance, simple motion estimation techniques (e.g., dead reckoning) or low-cost sensing solutions commonly integrated into mobile devices can be utilized for antenna localization. The SLAM problem can also be formulated by converting RFID measurements into relative tag-location constraints within a graph-based framework. Alternatively, EKF-SLAM can be applied using range and bearing measurements from responding tags. Furthermore, a Rao-Blackwellized particle filter can be used to automatically correct for the offsets' influence by suitably modifying the estimation of tag height, hence removing the requirement for offset estimates. On the other hand, asynchronous and chipless RFID infrastructure-based localization and tracking have a lot of potential for new real-world applications like SLAM systems [129].

4) RFID Integrated with SAR

This subsection provides a review of research publications on RFID localization integrated with SAR, followed by a summary of the lessons we have learned.

A. Surveyed Papers For a comparison between the use of multiple antennas and the single-antenna sensor fusion method for industrial RFID localization, see [12]. Using a sensor-fusion technique that combines phase data collected by onboard antennas from an infrastructure of passive reference tags with odometry data, the robot reconstructs its path. Next, using a multi-antenna SAR technique, it leverages its reconstructed trajectory to pinpoint target tags placed at unknown places. Unlike the previously suggested Interference SAR-based method, in [15] the authors limit the reader's sampling trajectory to a few approximative linear apertures, therefore extending its sampling trajectory to an arbitrary curve and improving accuracy. However, the study's strength is evident in the approach to position accuracy testing. The authors evaluated their system's accuracy using two methods: by measuring the absolute positioning error in *cm*-meters and comparing it with the tag's ground-truth location. This dual-method approach effectively demonstrates the system's ability to provide precise localization results.

Several prior works, including [128], [70], [111] have proposed 2D localization techniques based on the holographic approach, commonly known as SAR. Similar to the method presented in [15], these techniques rely on generating holographic images to locate RFID tags. Although creating multiple 2D images typically requires more time than scanning the entire 3D space, which can negatively impact real-time performance, the process is crucial for accurate localization. These methods involve constructing a spatial Probability Density Function (PDF) that represents the actual position of the RFID tag. The studies also explore how the displacement of the antenna phase center influences phase measurements, supported by experimental data to illustrate the extent of this effect. In addition to using odometric sensors for tracking, alternative solutions such as reference transponders or integrating inertial sensors with local positioning systems are considered in [128] providing further avenues for enhancing RFID localization accuracy. [70] describes and validates a new phase-based method for tracking and localizing objects that are attached to a conveyor belt and travelling along it.

B. Lessons Learned The size of the aperture is a crucial factor influencing localization accuracy. One of the highest achievable levels of accuracy, approximately 1 *cm*-meter, can be obtained using Synthetic Aperture (SA) methods, where refined localization is made possible through extended experiments with well-designed localization algorithms. As an industrial example, a UHF-RFID robotic system, where a mobile robot is equipped with multiple antennas for tagged-item inventory and localization, along with wheeled rotary encoders and an RFID reader, can be effectively supported by SAR-based methods With a single portable reader and antenna, the SAR-based localization process can be performed without requiring additional infrastructure or reference markers. During movement, the system measures the tag's phase at multiple positions to generate a set of holographic images. This implies that, as the device moves, an antenna array and corresponding phase measurements are generated. The coordinate system can be defined with its origin at the initial position of the device's aperture, while the final estimated location is determined relative to its most recent position, with the target's position evaluated in a 3D space. The primary disadvantage of this method lies in the fact that a mobile robot following a predefined curved trajectory was required to gather phase information, which limits flexibility in real-world applications. Synthetic-array phase-based methods have been shown to effectively detect RFID-tagged items along

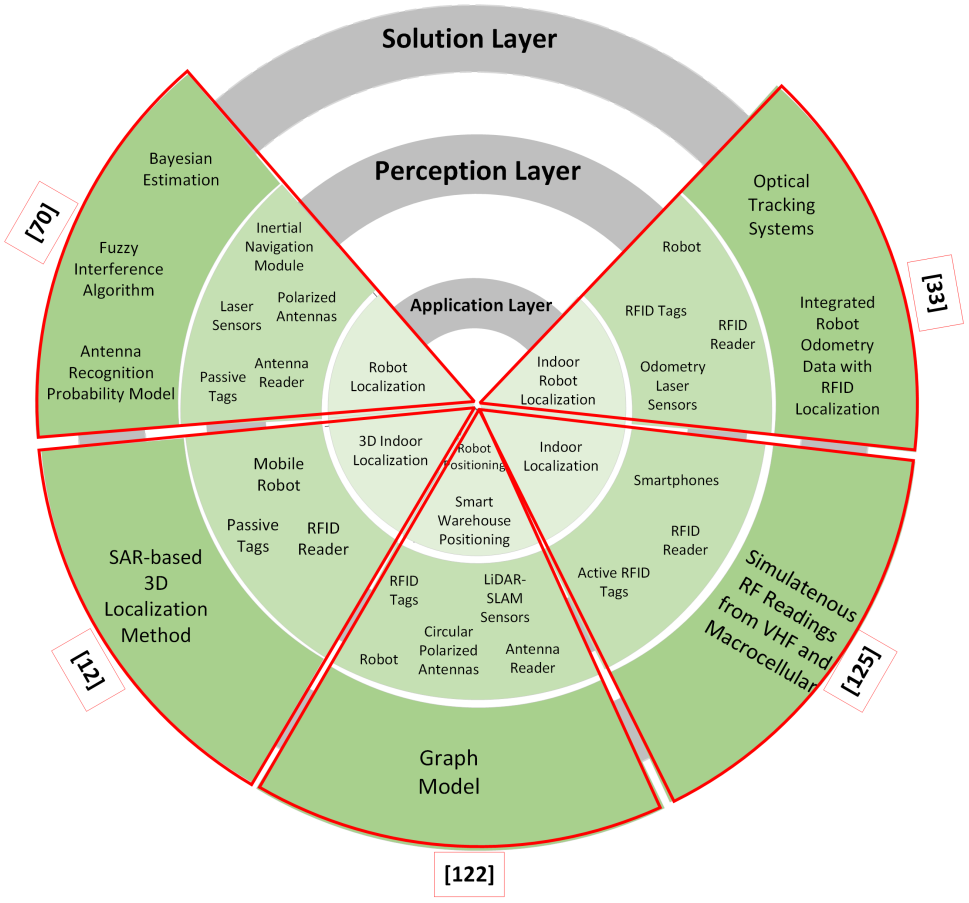


Fig. 7: Hybrid Fusion of Multiple Sensors and Antennas

complex paths, given sufficient simulated and measured data. The outcomes of several works show that the SAR method solution has great accuracy for both absolute and relative localization and is completely compliant with current industry standards. The SAR approaches can be seamlessly applied to surfaces with irregular shapes, making them highly suitable for challenging environments and specialized surfaces.

5) RFID Integrated with Other Technologies

Although we categorized major integrated technologies with RFID in previous sections, it is important to acknowledge that other valuable technologies should be considered in the context of localization. This section provides an assessment of research publications on RFID localization that integrate RFID with technologies like cellular networks and LiDAR, among others. Then we summarize the key lessons learned from these studies.

A. Surveyed Papers Temporal and statistical analyses of measurements from both technologies suggest that this hybrid approach can yield better localization outcomes by leveraging cellular information. [125] explores how cellular technologies like the Universal Mobile Telecommunications System and Global System for Mobile can be integrated with RFID-based localization to lower costs while enhancing accuracy. In the past few years, there has been some interesting research on LiDAR-integrated technology. For instance, a key advantage of the work by [32] is its emphasis on both 2D and 3D localization, presenting clear results for both dimensions.

Various methodologies for industrial localization leveraging RFID, integrated with laser sensors have been documented in recent studies with notable contributions reported in [126]. The fuzzy reasoning approach is used to compute the RFID antenna angle probability model when the robot finds an RFID tag. By using fuzzy reasoning, the antenna model related to the tag's normal angle is obtained, aiming to push the boundaries of the current antenna identification probability model. The application of RFID technology for positioning has been extensively explored in existing literature. Every RFID-based system's design for indoor person localization can be verified by simulations and real-world measurements conducted in different environments. [127] introduces a novel application in a museum setting, where the authors demonstrate the feasibility of tracking visitors' movements using a portable RFID reader.

B. Lessons Learned Industrial RFID localization systems integrate a variety of technologies, such as LiDAR, cellular networks, and lasers. It is important to note that WiFi-based solutions leverage existing networks for cost-effective localization, although these networks are typically designed for communication rather than positioning. For applications involving fast-moving vehicles, LiDAR, which relies on laser

sensors for range measurement, is advantageous. Robot localization that integrates RFID with laser data is a useful approach, particularly in industrial settings. Experimental findings indicate that integrating laser-detection data with RFID readings significantly enhances localization accuracy with a single RFID tag.

Cellular systems, on the other hand, often achieve lower localization precision, generally at the meter level. Modern wireless communication technologies like 5G, and future developments such as 6G (anticipated by 2030), offer promising alternatives to current cellular systems like Global System for Mobile and LTE for enhanced localization. In cellular networks, techniques such as proximity, RSS fingerprinting, and observed TDoA lateration have been applied for localization. For example, [92] explores WLAN-based solutions for computing 3D locations in multi-floor indoor environments. However, these methods, including recent developments in 5G localization, do not offer high precision. It is worth mentioning that both 5G and emerging 6G networks require careful design and management to ensure reliable and optimal connections between small cells and the macro network [130]. Leveraging satellite technology and phased array antenna systems enables robust communication for diverse mobile platforms, ranging from ground vehicles to aircraft. Beyond enabling navigation and telematics, these systems provide essential connectivity in scenarios where terrestrial networks are constrained, thereby bridging the coverage gap in isolated regions and maritime or aerial transit environments [131]. In environments such as warehouses, employing a fuzzy reasoning approach to model the RFID antenna angle probability enhances the system's ability to detect RFID tags and provides more accurate localization results. Maintaining low-latency connectivity for mobile platforms, such as automobiles, is complicated by path loss and the technical difficulty of dynamically aligning transmitter and receiver antenna beams. To address these challenges and meet the rising demand for high-speed data, mmWave phased array antennas are being integrated into satellite communication systems [132].

Tab.V presents a comprehensive overview of the surveyed RFID localization systems and their charactesristics. Our review reveals that WSNs are integrated in three studies, SLAM in five, SA techniques in five, LiDAR in one, cellular communication in one, laser-based methods in one, and wearable technology in one. From a measurement technique perspective, phase-based techniques are the most commonly employed, appearing in 21 papers, while RSS techniques are used in 10 systems. Additional methods include DoA, laser, and odometry data. Performance evaluation considers cost, speed, accuracy, coverage, robustness, and reliability, with accuracy being the only metric addressed by all systems, highlighting its importance. Notably, 24 of the 31 studies are recent, reflecting a focus on modern approaches. For consistency, original terminology from each study is preserved in the RFID Applications column, allowing for clarity in identifying the application focus of each system.

Fig.7 presents a comparison of five selected articles, highlighting the diversity of technologies and contributions, ranging from purely RFID-based systems to hybrid approaches that integrate cellular networks, WSN-RFID cooperation, SAR, laser sensors, and SLAM. The comparison is structured across three layers: the application layer, perception layer, and solution layer. The application layer outlines the various localization use cases, the perception layer identifies the components involved in sensing the physical environment, and the solution layer details the localization algorithms and techniques employed.

B. Statistical Evaluations of Existing Works

This section presents tables and figures that provide [3]insights into the surveyed works. RFID applications are categorized into three primary groups: robotics, smart items, and the IoT. Our focus on industrial RFID localization has led us to organize the applications under these categories. In Section II-D, we defined key concepts such as asset monitoring, product traceability, autonomous navigation, vehicular localization, and logistics management.

Fig.8 illustrates the varying levels of accuracy achieved in RFID localization across different studies. The chart captures the diversity of errors based on the technologies and methodologies used. The accuracy level is shown on the y-axis with localization accuracy divided into four main categories based on whether it is measured in *cm*-meters or meters and the integrated technology. It should be noted that the comparisons presented are indicative and qualitative, as the reported results are derived from different studies with varying experimental setups, parameter configurations, and evaluation conditions. Where exact values were unavailable (e.g., [32], [122] and [123] error bars were used to represent the reported performance ranges.

When employing WSN, localization accuracy is typically displayed in meters. In contrast, other systems achieve accuracy in *cm*-meters. We classify these technologies into four categories: solely RFID systems, SLAM and LiDAR, SA and SAR, and WSN. In the case of WSN systems, three studies [119], [118], and [107] provide meter-level accuracy. In the second bar chart, the accuracy level for studies using SA and SAR technologies is presented. Three studies [12], [15], and [111] fall under this category, with [111] demonstrating the highest level of accuracy, achieving less than 1 *cm* error after extensive testing. The third bar chart focuses on SLAM and LiDAR-based localization systems, showing *cm*-level accuracy for five studies [32], [121], [122], [123], and [124]. The fourth and final bar chart illustrates the accuracy of eight "solely RFID" systems not integrated with other technologies, many of which demonstrate high accuracy. Additionally, some works report results using cumulative distribution functions or average localization errors under different tag and antenna configurations [30], [112], [114], [17], [115], which are excluded from the figure.

Fig.9 illustrates the percentage distribution of various algorithms used in the literature for optimal localization estimation

[3]While accuracy is the primary focus due to its consistent reporting across studies, other KPIs (e.g., cost, robustness, reliability, and coverage) are influenced by hardware and vendor-specific factors, making direct comparisons more challenging.

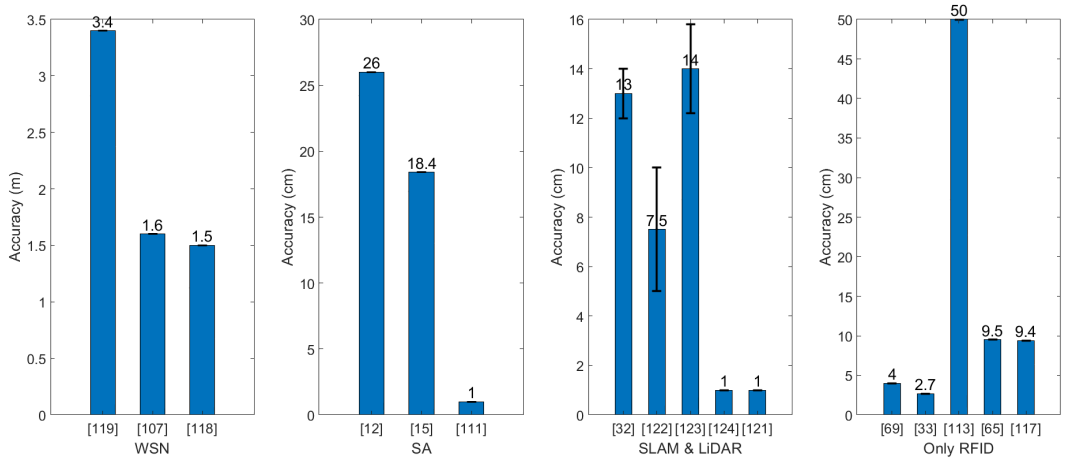


Fig. 8: Obtained Accuracy in the RFID Localization Works

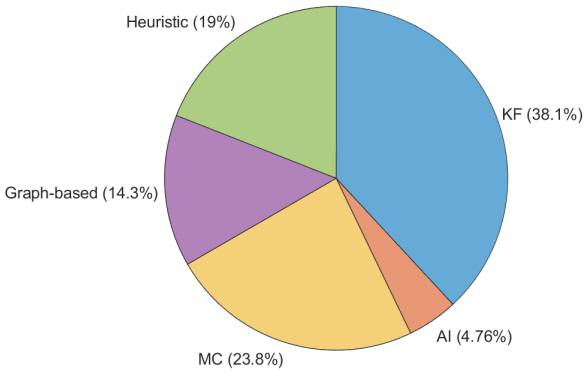


Fig. 9: Applied RFID Localization Algorithms

and intersection quality assessment. These algorithms are categorized into five main groups. The first group includes KF variants, such as hyrid cooperative EKF, predictive EKF, quantized EKF, predictive KF, multi-hypothesis EKF, and EKF-SLAM. The second group consists of AI-based solutions, including SMO. The third group covers graph-based solutions like multidimensional scaling, and the fourth group includes particle filters and MC methods. Lastly, heuristic algorithms such as greedy algorithms and iterative refinement make up the fifth group. KF-based methods are the most widely used, representing 38.1 percent of the surveyed literature, with eight research articles highlighting their application.

The MC method and PF algorithm, grouped under the ”MC” category, appear in five publications and account for 23.8% of the pie chart, making it the second-largest category. While the MC simulation is a probabilistic model that incorporates uncertainty into its predictions, the PF algorithm employs a sequential MC approach to identify the innovations driving a stochastic process, updating the state estimate recursively based on a sequence of observations. The graph-based category, including graph-based solutions and multidimensional scaling algorithms, represents 14.3 % of the literature with three studies. The AI category, comprising 4.76 percent of the pie chart, includes ML and statistical learning algorithms such as NN, SVM, KNN, and Bayesian algorithms. These algorithms incorporate various dependencies within the measurement model to enhance performance and utilize collected data to estimate the operator's distance and angle. Heuristic algorithms account for 19 percent of the total publications, with four papers using methods like the RTL method in [109] the greedy algorithm in [17], the heuristic multi-frequency algorithm in [117], or the iterative refinement algorithm in [111]. It is important to note that some publications employ experimental methods or unique algorithms that do not fit within the main categories. From an algorithmic standpoint, these algorithms do not necessarily belong to any specific subset of the most recent localization techniques.

Fig.10 presents a heatmap that highlights the best accuracy achieved by various technologies in relation to the measurement techniques used. A standout example is from the study by [121], which demonstrates a *cm*-level accuracy using a robust 2D localization method. This approach utilizes a phase-distance model, SA techniques, and phase unwrapping to address challenges like multipath interference and phase ambiguity. The experimental tests, conducted with a mobile robot equipped with a reader antenna and using SLAM techniques, show effective tag localization and environmental mapping. Similarly, [111] reports exceptional results, achieving less than 1 *cm* localization errors across various mainstream tag types. The heatmap underscores that technologies like SLAM and SAR consistently outperform others in terms of precision, reinforcing their suitability for high-accuracy RFID localization applications.

Fig.11 presents a qualitative comparison of the expected performance of RFID integrated localization technologies across common operating conditions. Multipath resistance, harsh environments, indoor and outdoor operation, and LoS/NLoS performance are among the most important factors when selecting an integrated technology. SAR and SLAM yield the strongest

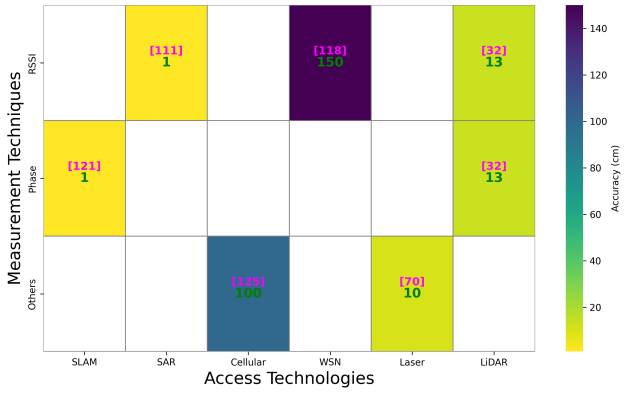


Fig. 10: Heatmap of Best Obtained Accuracy

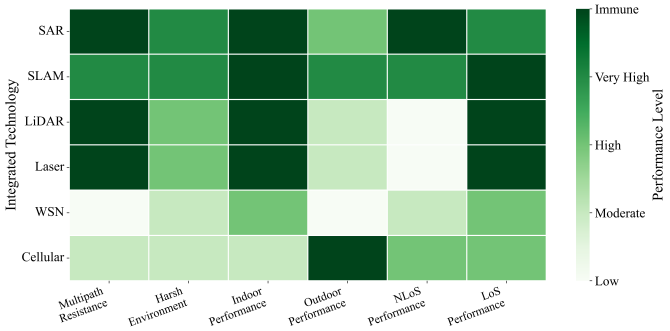


Fig. 11: Qualitative Comparison of RFID Integrated Localization Technologies Under Different Operating Conditions.

overall performance across these metrics. Conversely, LiDAR and Laser-based integrations excel in indoor, LoS scenarios but suffer under NLoS conditions, while cellular technology provides superior outdoor coverage, and WSNs offer broad coverage for indoor scenarios. It should be noted, however, that all integrated technologies have a minimum performance level, and the actual performance ultimately depends on the design and configuration of the overall system. Complementing this comparison, Fig.12 illustrates the trade-offs between deployment cost, coverage, and robustness. As shown, no single technology consistently outperforms the others across all three metrics. Instead, each technology offers different trade-offs, and the most suitable choice depends on the specific deployment requirements and application priorities. Specifically, cellular networks and WSNs provide the maximum operational coverage, while LiDAR and Laser technologies occupy the higher end of the cost spectrum. For applications prioritizing robustness, SAR emerges as the most effective option. The assigned scores are intended solely for qualitative comparison and do not represent absolute values. Actual performance depends on the design and configuration of the overall system.

C. Lessons Learned

To enable large-scale tag deployments and support both 2D and 3D localization, an RFID localization system, depending on its design goals, can offer a variety of benefits. These include high reliability, broad coverage, performance evaluation through simulation and experimentation, reduced steady-state error, effective localization algorithms, and robust operation in cluttered environments. However, each system may also come with specific challenges that need to be carefully considered. Tracking trajectory data in experiments might not be as accurate as simulations, leading to serious errors. As another illustration, irregular tag layouts might impact the level of accuracy needed in particular settings, and several noise sources can cause problems with phase measurement.

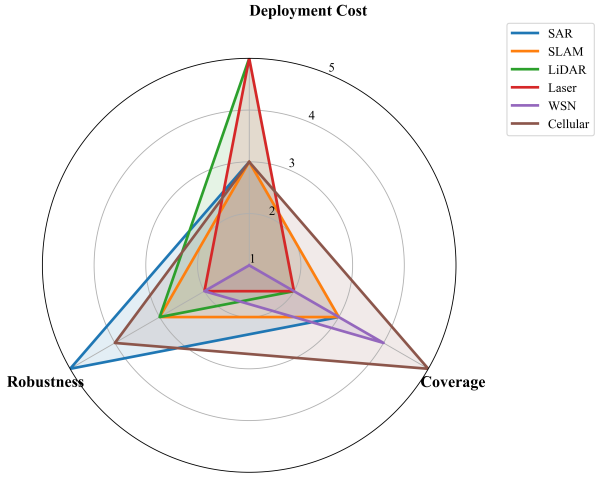


Fig. 12: Comparison of RFID Integrated Localization Technologies in Terms of Deployment Cost, Coverage, and Robustness.

Several approaches are explored to overcome different challenges, such as the EKF-based hybrid cooperative positioning method combined with multidimensional scaling, Cramer-Rao Bound analysis, etc. Other techniques include intersection multidimensional feature analysis, fuzzy localization derived from radio tomographic imaging results, and solutions for passive UHF RFID localization using phase and RSSI data. These methods, including phase unwrapping and filtering via discrete wavelet transforms, can be further enhanced by integrating multiple technologies and strategies. Hybrid fusion of multiple sensors provides a practical way to compare various measurement techniques, with trials in both simple warehouse settings and more complex environments. When technologies like SLAM, SAR, cellular, WSN, laser, and LiDAR are combined, these systems can achieve the highest level of precision.

The surveyed studies also highlight common trends in the performance metrics used to evaluate RFID localization systems. Tab. V summarizes the performance metrics reported across the surveyed studies. As shown, localization accuracy is the most frequently reported metric, followed by cost, speed, and robustness. While *cm*-level accuracy is achievable in controlled environments, larger localization errors are generally observed in large-scale or multipath environments. Approximately 13% of the surveyed studies evaluate localization accuracy using RMSE or mean distance error, while CDF-based error comparison analysis of different parameter errors is commonly adopted in industrial RFID localization and ac-

counts for about 26% of all research works. On the other hand, more than 60% of the works focused primarily on estimation error, average error, or accuracy in 2D/3D for the designed system. Besides localization accuracy, a smaller number of studies additionally report localization robustness (about 13%), cost (about 30%), reliability (about 6%), coverage (about 6%), or speed (more than 22%), depending on the target application.

V. Research Challenges and Future Directions

The future paths of mmWave RFID technology solutions, AI-based localization, RFID-based AR localization, non-line of sight signaling, UWB RFID solutions, and RFID used for DT are the main topics of discussion in this space.

A. Ultra-wideband RFID Solutions

Since the Federal Communications Commission allocated 7.5 GHz of spectrum (3.1–10.6 GHz) for UWB in 2002, the technology has gained increasing attention. UWB systems spread their signal over a wide frequency range, typically exceeding 500 MHz, by using narrow time-domain pulses of very short duration, often around a nanosecond. This makes UWB particularly suitable for high-definition indoor tracking applications [5]. Given the strengths of UWB, integrating UWB with RTLS and RFID technologies has become a promising approach to improving the benefits of both systems. Several studies have explored this integration, particularly in the context of active UWB-RFID solutions [10], [133] and [134]. The energy efficiency and environmental compatibility of UWB-RFID systems have been further examined by some projects, such as the GRETA project [135]. One major advantage of impulse radio UWB is its ability to estimate ToA with fine resolution, leading to *cm*-level accuracy in range estimation [136] , [137]. Also, the development of the IEEE 802.15.4f standard, which focuses on providing precise indoor positioning and tracking with low-cost, energy-efficient tags, has been significantly shaped by proprietary UWB solutions for RTLS [138].

Current 3GPP ideas and experimental findings on long-distance tag reading with 5G signals. In order to create an efficient method of connecting IoT devices without the need for specialized readers like in RFID systems, a closer relationship between RFID and cellular technology has been envisioned. Using new technologies like reconfigurable intelligent positioning with improved RFID systems' surfaces, 3GPP is currently investigating the possibility of interrogating passive tags by backscattering 5G-like signals, also known as BackCom, which has attracted a lot of attention lately. While localization capabilities of 5G-based BackCom systems remain underexplored, early 5G-compatible implementations demonstrate energy-autonomous, long-range mmWave RFID sensing for IoT applications. There are additional advantages to using super wideband communication devices and systems. Some of the initially benefits of high-performance networks and super ultra-wideband are contested in [139], by robotics, indoor wireless localization, driverless cars, and Virtual Reality (VR). According to some research, the antenna's small size, cost-effective simplicity of structure, versatility, and efficiency, especially when compared to more complex antennas, allow it to be utilized in a wide range of frequencies, including 5G networks. Its enhanced radiation patterns also make it a suitable candidate for UWB and super wideband applications [140]. Another fascinating subject that may have an impact on the accuracy of UWB RFID systems is antenna design for 6G wireless communications. Also some of the recent works have study on ambient power-enabled IoT.

Despite these advancements, UWB-RFID technology is not yet fully mature for widespread use in context-aware applications. Several challenges remain, many of which are similar to those faced by UHF RFID technology, and must be addressed for UWB-RFID to become a widely adopted solution. UWB technology achieves exceptional localization accuracy, but it remains significantly more expensive than alternative positioning methods. This higher financial burden stems from both the hardware components and the intricate installation process. The specialized UWB chips, which generate and interpret nanosecond radio pulses, are technologically complex and costly, with fixed anchors (receivers) demanding even higher investments. Furthermore, obtaining precise 2D or 3D coordinates requires a continuous LoS between a tag and at least three or four anchors, necessitating a much denser network than other technologies. The system also requires exact clock synchronization among these anchors. Consequently, for industrial RFID applications such as general pallet tracking in large warehouses, solely RFID offers far more cost-effective alternatives, as meter- or zone-level accuracy is often sufficient. For the reasons outlined above, none of the selected studies in our review employed UWB for indoor localization. Nevertheless, we consider it important to highlight UWB as a promising and highly relevant direction for future research.

B. mmWave RFID Solutions

Millimeter waves represent one of the main technologies for the application deployment of RFID in the future. Smartphones of the upcoming next generation (6G) will incorporate mmWave interfaces to increase the data throughput of connections to over 1 Gbps. Distributed antenna systems, commonly used in 5G and 6G networks to enhance data capacity [130], can also be considered for RFID localization. In addition to the enormous bandwidth that is available at such frequencies, which is advantageous for precise positioning, mmWave technologies have additional intriguing possibilities. Numerous antenna elements can be packed into a compact space and are even integrated into smartphones because of the short signal wavelength. Due to the formation of the incredibly narrow beam, it will be feasible to focus the power flux towards the tag and transfer the energy over a distance of several meters with significantly greater efficiency than is currently conceivable with available technology. The large antenna arrays currently used for communication might be used as reference nodes, removing the need for specialized equipment and allowing precise ToA and AoA estimates [10].

Another possible scenario is that access points set up for indoor communications and outfitted with mmWave antenna arrays localize the tags that are already present in the area. It

then focuses the beam so that the tags can build up energy (for example, at night) and become operational whenever a mobile device interrogates them [141]. Five important mmWave positioning points are high carrier frequencies, large bandwidths, a large number of antennas, device-to-device communications, and network densification [142]. mmWave frequency use results in greater fading and losses as well as improved sensitivity to blockage, which calls for completely new physical layer communication paradigms [143]. Van Atta arrays have recently been explored for highly accurate localization of low-power tags over extended distances. Some of the works address the challenge of efficiently localizing roadside infrastructure, such as lane markers and road signs, in the context of autonomous driving, using standard automative radars operating at mmWave frequencies. The author reported experimental results demonstrating on operating range of 100m with *cm*-level localization accuracy using a VanAtta ultra-low-power tag [144], [145].

Self-conjugating metasurfaces combined with retro-directive backscattering can be used to achieve low-complexity MIMO grant-free random access communications. This plan is especially appealing for 6G applications like the industrial IoT, where MIMO networks need to be set up with minimal latency and little overhead in order to compensate for path loss at high frequencies. In addition, it facilitates grant-free transmission of brief packets by sensors with incredibly low complexity and low energy usage [146]. Also [147] suggest using a retro-directive antenna array at the user equipment side, allowing the signal provided by the base station to be conjugated and phase-modulated based on the user equipment data and then reflected back towards the source. It is demonstrated that, in single and multi-user MIMO scenarios, ultra-low complexity user equipments can quickly and automatically establish parallel communication links with the base station by using modified power methods to compute the eigenvectors of the resulting round-trip channel.

C. Augmented Reality Localization using RFID

Beyond improving standalone RFID localization accuracy, a promising direction is its integration with AR and VR, where localization results enable interactive spatial awareness rather than simple position estimates. Prior works have explored RFID–AR synergy in applications such as object recognition, annotation [148], [149], and AR-assisted item search [150], [151]. These approaches combine RFID's robustness to occlusion with intuitive AR-based visualization. More recent developments, including mmWave and 5G-enabled RFID architectures, aim to support higher spatial resolution and immersive AR/VR applications [152]. However, AR is still largely used as a visualization layer, with limited impact on the underlying localization algorithms, which are often evaluated in controlled environments with low tag density.

The limitations of current RFID-enabled AR systems highlight several open research directions. First, there is limited integration between RFID localization models and AR tracking frameworks, as most approaches loosely combine RF measurements with vision-based pose estimation, making them sensitive to drift, multipath effects, and environmental dynamics. Second, scalability remains a challenge, as many systems assume sparse tag deployments and low interference, restricting applicability in large-scale or cluttered environments. While mmWave RFID architectures offer higher spatial resolution, they introduce challenges related to hardware complexity, energy consumption, antenna integration, and blockage sensitivity. Additionally, practical deployment raises concerns about user trust, safety, and privacy due to potential localization inaccuracies and non-line-of-sight sensing. Addressing these issues requires jointly designed RFID–AR systems that integrate RF sensing, AR tracking, uncertainty modeling, and human interaction for robust and scalable performance.

D. AI-based Localization using RFID

Beyond advances in physical-layer modeling and signal processing, a key future direction for RFID localization is the integration of AI and ML to address the variability of RF environments. Existing work shows that AI can enhance performance across the localization pipeline, from classical ML in fingerprinting to learning-based error compensation that reduces estimation errors without modifying core algorithms [153]. Edge-AI approaches further enable low-latency deployment near RFID readers [154]. AI-powered RFID systems have also been applied in large-scale settings such as smart retail, combining real-time tracking with ML-based prediction for localization and system optimization [155]. Additionally, AI-driven RFID research in activity recognition demonstrates the ability of deep learning to extract robust spatial–temporal features from noisy RF signals [156], highlighting its potential for complex sensing tasks.

Despite these advances, several limitations highlight key directions for future research in AI-enabled RFID localization. Many learning-based methods remain environment-specific, relying on labeled data and showing limited generalization under changing conditions [157], [154]. In addition, AI models are often used as black-box regressors on top of traditional methods, with limited interpretability and weak integration of RF constraints [153]. From a systems perspective, deploying complex models raises concerns about computational cost, energy consumption, and latency, especially for edge devices and battery-less infrastructures [155]. Performance degradation under distribution shifts, such as multipath effects or varying tag density, is also largely overlooked. These challenges motivate hybrid model- and data-driven approaches, where AI supports adaptive correction and uncertainty modeling while respecting RF principles. Promising directions include transfer and self-supervised learning, explainable and uncertainty-aware models, and scalable edge-AI solutions for dynamic real-world deployments.

E. RIS-assisted RFID Localization

An emerging direction for RFID localization is the use of RISs to actively shape the propagation environment and improve observability in challenging scenarios. Recent studies show that RIS-assisted localization can enhance spatial observability by creating controllable multipath diversity without

requiring additional active anchors [158], [159], [160], [161], [162]. By dynamically steering electromagnetic waves, RISs help mitigate blockage and NLoS conditions while extending coverage in cluttered indoor environments [159]. When combined with ML techniques, they enable accurate localization even where conventional RFID systems struggle. Additionally, the passive nature of RISs makes them suitable for energy-efficient, large-scale deployments [163]. Overall, these works establish RISs as a promising environmental control mechanism for next-generation RFID localization systems.

At the same time, RIS-assisted approaches reveal several limitations that motivate future research. Many existing works assume accurate RIS configuration, synchronization, and static environments, which are difficult to ensure in large-scale RFID deployments with passive tags. RIS-enabled localization introduces challenges such as calibration overhead, phase-quantization errors, and sensitivity to blockage. From an algorithmic perspective, reliance on supervised learning or offline optimization raises concerns about generalization and scalability. These challenges highlight the need for jointly designed RIS–RFID frameworks that integrate RIS control, RF feature extraction, and inference under practical constraints. Promising directions include adaptive and uncertainty-aware RIS configuration, hybrid model- and data-driven approaches, and lightweight implementations for real-world deployments.

F. RFID Localization and Digital Twin Integration

Beyond improving pointwise localization accuracy, an important direction for RFID localization is its integration with DTs, where localization data continuously updates virtual representations of physical environments. Existing studies demonstrate the feasibility of using RFID localization as a sensing layer for DTs, particularly in retail and logistics. For example, RFID-based localization enables real-time tracking of item positions in retail environments [164], [165], while mobile RFID robots can capture spatial data to support DT visualization and decision-making [166]. More recent work explores RFID-based 3D localization for modeling industrial processes such as order picking [167]. Overall, these studies highlight RFID localization as a cost-effective solution for maintaining spatial consistency between physical systems and their digital counterparts.

However, the surveyed literature reveals several limitations at the intersection of RFID localization and DTs. Many systems rely on coarse-grained localization, controlled layouts, or static assumptions, limiting fidelity and scalability. Localization errors, intermittent reads, and latency can propagate into the DT, leading to inconsistent virtual states. Integrating continuous RFID data also raises challenges in synchronization, scalability, and model updating, particularly in dynamic environments. Additional concerns include deployment complexity and reliance on auxiliary infrastructure. These issues highlight the need for robust, real-time coupling between RFID localization and DT management, including uncertainty-aware methods, event-driven updates, and scalable representations. Addressing these challenges is essential for enabling reliable, real-world RFID-powered DT systems.

VI. Conclusion

This survey has provided a comprehensive review of RFID-based localization systems, highlighting both traditional and emerging approaches within the evolving landscape of industrial applications. We explored various localization methods, including fingerprinting, non-fingerprinting, Bayesian tracking models, and hybrid fusion of multiple sensors, and emphasized their integration with complementary technologies. In addition to classifying these existing technologies, we also used these methods to compare algorithms in AI-based solutions, graph-based localization algorithms, KF, heuristic-based solutions, and MC localization techniques as well as presenting many lesson learned relevant to each of them that are useful for system design and assessments that are missing in the literature. We display charts and tables, evaluate the surveyed works, and provide statistical insights. We classified and analyzed the published works in a variety of ways, including achieved accuracy in the RFID localization works, the percentage of applied RFID localization algorithms, best achieved accuracy by various technologies in relation to the measurement techniques, qualitative comparison of RFID integrated localization technologies across operating conditions and the trade-off between different metrics. After that, we wrapped up our survey by outlining unsolved problems, difficulties, and potential paths of exploration and exciting opportunities for further innovation in the field. Finally, we discuss the challenges and future directions of integrating RFID with advanced technologies such as UWB, mmWave, AI, DT, AR, and RIS, highlighting their potential to enhance localization accuracy, scalability, and cost-effectiveness in diverse industrial environments.

Acknowledgment

Special gratitude to the national Belgium project Blueprint for Excellence and Leadership in 6G through Interregional Concerted Action (BEL6GICA) for providing financial assistance for this research at the University of Mons, Belgium, at the time that this work was being completed.

References

[1] A. Mansour, J. Ye, Y. Li, H. Luo, J. Wang, D. Weng, and W. Chen, "Everywhere: A framework for ubiquitous indoor localization," *IEEE Internet of Things Journal*, vol. 10, no. 6, pp. 5095–5113, 2023.

[2] F. Furfari, A. Crivello, P. Baronti, P. Barsocchi, M. Girolami, F. Palumbo, D. Quezada-Gaibor, G. M. Mendoza Silva, and J. Torres-Sospedra, "Discovering location based services: A unified approach for heterogeneous indoor localization systems," *Internet of Things*, vol. 13, p. 100334, 2021.

[3] Y. Pinar, A. Zuhair, A. Hamad, A. Resit, K. Shiva, and A. Omar, "Wireless sensor networks (wsns)," in *2016 IEEE Long Island Systems, Applications and Technology Conference (LISAT)*, 2016, pp. 1–8.

[4] R. . Verdone, D. Dardari, G. Mazzini, and A. Conti, *Wireless Sensor and Actuator Networks: Technologies, Analysis and Design*. Elsevier Science, 2010.

[5] D. Dardari, P. Closas, and P. M. Djurić, "Indoor tracking: Theory, methods, and technologies," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 4, pp. 1263–1278, 2015.

[6] S. Liu and T. Nakanishi, "Obstacles detection and motion estimation by using multiple lidar sensors data," in *2022 13th International Congress on Advanced Applied Informatics Winter (IIAI-AAI-Winter)*, 2022.

[7] T. Kim and T. Park, "Calibration method between dual 3d lidar sensors for autonomous vehicles," in *2017 56th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, 2017.

[8] A. Moreira, P. Prats-Iraola, M. Younis, G. Krieger, I. Hajnsek, and K. P. Papathanassiou, "A tutorial on synthetic aperture radar," *IEEE Geoscience and Remote Sensing Magazine*, 2013.

[9] J. Kim, S. Kim, W. Lee, S. Shin, Y. Choi, and M.-H. Ka, "Design and implemetation of compact 77 ghz synthetic aperture radar for drone based applications," in *2019 6th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, 2019.

[10] D. Dardari, N. Decarli, A. Guerra, and F. Guidi, "The future of ultra-wideband localization in rfid," in *2016 IEEE International Conference on RFID (RFID)*, 2016, pp. 1–7.

[11] M. A. Varner and G. D. Durgin, "Achieving long-range ambient scatter communication networks: A primary user interference perspective," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 3, pp. 324–330, 2021.

[12] A. Motroni, F. Bernardini, A. Buffi, P. Nepa, and B. Tellini, "A uhf-rfid multi-antenna sensor fusion enables item and robot localization," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 456–466, 2022.

[13] C. Qi, F. Amato, B. Kihei, and G. D. Durgin, "Fine-scale phase-based ranging through walls and obstructions using tunneling rfid tags," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 4, pp. 397–406, 2021.

[14] C. Qi, F. Amato, M. Alhassoun, and G. D. Durgin, "A phase-based ranging method for long-range rfid positioning with quantum tunneling tags," *IEEE Journal of Radio Frequency Identification*, vol. 5, no. 2, pp. 163–173, 2021.

[15] X. Liang, Z. Huang, S. Yang, and L. Qiu, "E3dinsar: 3-d localization of rfid-tagged objects based on interference synthetic apertures," *IEEE Internet of Things Journal*, vol. 7, no. 12, pp. 11 656–11 666, 2020.

[16] M. Alotaibi, M. Murad, S. A. H. Alhuthali, F. R. Al-Osaimi, and F. Aldosari, "Mimo radio frequency identification: A brief survey," *Sensors*, vol. 22, no. 11, 2022.

[17] A. Diallo, Z. Lu, and X. Zhao, "Wireless indoor localization using passive rfid tags," *Procedia Computer Science*, vol. 155, pp. 210–217, 2019, the 16th International Conference on Mobile Systems and Pervasive Computing (MobiSPC 2019),The 14th International Conference on Future Networks and Communications (FNC-2019),The 9th International Conference on Sustainable Energy Information Technology.

[18] A. Motroni, A. Buffi, P. Nepa, and B. Tellini, "Sensor-fusion and tracking method for indoor vehicles with low-density uhf-rfid tags," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–14, 2021.

[19] A. Motroni, A. Buffi, and P. Nepa, "A survey on indoor vehicle localization through rfid technology," *IEEE Access*, vol. 9, pp. 17 921–17 942, 2021.

[20] S. I. Khan, B. R. Ray, and N. C. Karmakar, "Rfid localization in construction with iot and security integration," *Automation in Construction*, vol. 159, p. 105249, 2024.

[21] C. Li, L. Mo, and D. Zhang, "Review on uhf rfid localization methods," *IEEE Journal of Radio Frequency Identification*, vol. 3, no. 4, pp. 205–215, 2019.

[22] E. Pereira, i. Araujo, L. F. V. Silva, M. Batista, S. Junior, E. Barboza, E. Santos, F. Gomes, I. T. Fraga, R. Davanso, D. O. d. Santos, and J. d. A. Nascimento, "Rfid technology for animal tracking: A survey," *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 609–620, 2023.

[23] J. Xu, Z. Li, K. Zhang, J. Yang, N. Gao, Z. Zhang, and Z. Meng, "The principle, methods and recent progress in rfid positioning techniques: A review," *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 50–63, 2023.

[24] R. Buettner, T. Clauß, M. T. Huynh, and D. Koser, "Rfid tracking and localization technologies in healthcare," in *2020 IEEE Symposium on Industrial Electronics & Applications (ISIEA)*, 2020, pp. 1–5.

[25] G. M. Bianco and G. Marrocco, "Radio frequency identification and localization by wearable lora for search and rescue in mountains," in *2022 IEEE International Conference on RFID (RFID)*, 2022, pp. 120–125.

[26] A. Haibi, K. Oufaska, K. E. Yassini, M. Boulmalf, and M. Bouya, "Systematic mapping study on rfid technology," *IEEE Access*, vol. 10, pp. 6363–6380, 2022.

[27] C. Boyer and S. Roy, "Coded qam backscatter modulation for rfid," *IEEE Transactions on Communications*, vol. 60, no. 7, pp. 1925–1934, 2012.

[28] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 2889–2922, 2018.

[29] V. Iyer, V. Talla, B. Kellogg, S. Gollakota, and J. Smith, "Inter-technology backscatter: Towards internet connectivity for implanted devices," in *Proceedings of the 2016 ACM SIGCOMM Conference*, ser. SIGCOMM '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 356–369.

[30] C. Tian, Y. Ma, and B. Wang, "Cooperative localization for passive rfid backscatter networks and theoretical analysis of performance limit," *IEEE Transactions on Wireless Communications*, vol. 22, no. 2, pp. 1388–1402, 2023.

[31] E. Di Giampaolo, F. Martinelli, and F. Romanelli, "The role of the rfid polarization mismatch in the simultaneous localization and mapping problem," *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 475–485, 2023.

[32] Z. Liu, Z. Fu, T. Li, I. H. White, R. V. Penty, X. Yang, R. Du, and M. Crisp, "A phase and rssi-based method for indoor localization using passive rfid system with mobile platform," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 544–551, 2022.

[33] C. Kammel, T. Kögel, M. Gareis, and M. Vossiek, "A cost-efficient hybrid uhf rfid and odometry-based mobile robot self-localization technique with centimeter precision," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 467–480, 2022.

[34] P. S. Sharakhin, A. V. Levchenko, and D. A. Renzhin, "Comparing efficiency of outsourcing or insourcing digital logistics in supply chain management," in *2021 International Conference on Quality Management, Transport and Information Security, Information Technologies (IT&QM&IS)*, 2021, pp. 716–718.

[35] E. T. GANG YANG, GARY ANDERSON, "A rfid landmark navigation auxiliary system," in *World Automation Congress (WAC)*, 2006.

[36] A. Dimitriou, A. Tzitzis, A. Filotheou, and S. Megalou, "Autonomous robots, drones and repeaters for fast , reliable, low-cost rfid inventorying & localization," in *6th International Conference on Smart and Sustainable Technologies (SpliTech)*, 2021.

[37] S. Susi, Cristini and Daddario, "A low-cost indoor and outdoor terrestrial autonomous navigation model." IEEE, 22nd Telecommunications forum TELFOR, 2014.

[38] Y. Zhang, Y. Ma, K. Liu, J. Wang, and S. Li, "Rfid based vehicular localization for intelligent transportation systems," in *IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2019.

[39] X. Zhou, "The probes into the innovation direction of modern logistics management mode in artificial intelligence era," in *2021 International Conference on Computer Information Science and Artificial Intelligence (CISAI)*, 2021, pp. 855–859.

[40] M. R. Alain Edwards, Imad Mahgoub, "Investigation of rfid based localization for smartdrive vehicular network testbed," in *IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON)*, 2016.

[41] D. Zhang, L. Tianruo, M. Chen, S. Zhao, M. Guo, and Y. Zhang, "Real-time locating systems using active rfid for internet of things," in *IEEE Systems Journal (Volume: 10, Issue: 3)*, 2016.

[42] S. Sugumar, V. Aishwarya, B. R. Govardhan, G. Sir, and G. Hariharan, "Asset tracking and monitoring using rfid technology for industries," in *7th International Conference on Design Innovation for 3 Cs Compute Communicate Control (ICDI3C)*, 2023.

[43] R. Patil, S. Nema, and S. Kadam, "Radio frequency identification system for asset tracking and inventory management in hospitals," in *4th International Conference on Signal Processing and Integrated Networks (SPIN)*, 2017.

[44] M. Caracciolo, O. Casciotti, C. Lloyd, E. Sola-Thomas, M. Weaver, K. Bielby, M. A. B. Sarker, and M. H. Imtiaz, "Autonomous navigation system from simultaneous localization and mapping," in *2022 IEEE 31st Microelectronics Design & Test Symposium (MDTS)*, 2022, pp. 1–4.

[45] L. M. Trujillo, J. A. García, D. Lizcano, and M. Mejías, "Traceability management of systems of systems: A systematic review in the assisted reproduction domain," in *Journal of Web Engineering*, 2019.

[46] Y. Zhang, M. Jin, G. Zheng, and H. Li, "Design and application of product traceability blockchain-based platform," in *2020 3rd International Conference on Smart BlockChain (SmartBlock)*, 2020, pp. 125–131.

[47] C. K. M. Lee, C. M. Ip, T. Park, and S. Chung, "A bluetooth location-based indoor positioning system for asset tracking in warehouse," in *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 2019, pp. 1408–1412.

[48] A. Arboleya, J. Laviada, Y. Álvarez López, and F. Las-Heras, "Real-time tracking system based on rfid to prevent worker–vehicle accidents," in *IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS*, 2021.

[49] F.-K. Chen, H.-P. Lin, and T.-S. Hsu, "A novel approach to high performance of rfid-based asset tracking in a metal cabinet," in *25th International Conference on Mechatronics Technology (ICMT)*, 2022.

[50] E. Hatem, E. Colin, S. Abou-Chakra, B. El-Hassan, and J.-M. Laheurte, "New empirical indoor path loss model using active uhf-rfid tags for localization purposes," in *2018 IEEE International Conference on RFID Technology & Application (RFID-TA)*, 2018, pp. 1–6.

[51] J. Su, A. X. Liu, Z. Sheng, and Y. Chen, "A partitioning approach to rfid identification," *IEEE/ACM Transactions on Networking*, vol. 28, no. 5, pp. 2160–2173, 2020.

[52] J. Zhu, G. Chen, G. Tian, and H. Liu, "Underground passive lf rfid localization method based on magnetic field model of reader coil antenna," *IEEE Transactions on Instrumentation and Measurement*, vol. 73, pp. 1–10, 2024.

[53] K. Chawla, C. McFarland, G. Robins, and C. Shope, "Real-time rfid localization using rss," in *International Conference on Localization and GNSS (ICL-GNSS)*, 2013.

[54] S. Parlak and I. Marsic, "Non-intrusive localization of passive rfid tagged objects in an indoor workplace," in *2011 IEEE International Conference on RFID-Technologies and Applications*, 2011, pp. 181–187.

[55] T. Nick, G. Smietanka, and J. Götze, "Rss-based channel measurements and their influence on localization in rfid applications," in *IEEE International Symposium on Consumer Electronics (ISCE)*, 2013.

[56] F. Zampella, A. Ramón Jiménez Ruiz, and F. Seco Granja, "Indoor positioning using efficient map matching, rss measurements, and an improved motion model," in *IEEE Transactions on Vehicular Technology*, 2015.

[57] Z. Zhang, Z. Lu, V. Saakian, X. Qin, Q. Chen, and L.-R. Zheng, "Item-level indoor localization with passive uhf rfid based on tag interaction analysis," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 4, pp. 2122–2135, 2014.

[58] J. Shen, A. F. Molisch, and J. Salmi, "Accurate passive location estimation using toa measurements," in *IEEE Transactions on Wireless Communications (Volume: 11, Issue: 6)*, 2012.

[59] Y. Qi, P. Luo, C. XU, J. Wan, and J. He, "Target localization in industrial environment based on toa ranging," in *IEEE, 28th Wireless and Optical Communications Conference (WOCC)*, 2019.

[60] Y. Cheng and T. Zhou, "Uwb indoor positioning algorithm based on tdoa technology," in *10th International Conference on Information Technology in Medicine and Education*, 2019.

[61] R. Mo, Y. Pei, S. Sun, A. B. Premkumar, and N. V. Venkatarayalu, "Deep machine learning-based aod map and aoa map construction for wireless networks," in *2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring)*, 2024.

[62] G. K. J. Fischer, T. Schaechtle, A. Gabbrielli, J. Bordoy, I. Häring, F. Höflinger, and S. J. Rupitsch, "A systematic survey and comparative analysis of angular-based indoor localization and positioning technologies," *IEEE Communications Surveys & Tutorials*, vol. 28, pp. 3830–3869, 2026.

[63] J. Zhou, H. Zhang, and L. Mo, "Two-dimension localization of passive rfid tags using aoa estimation," in *2011 IEEE International Instrumentation and Measurement Technology Conference*, 2011, pp. 1–5.

[64] Y. Ma, B. Wang, S. Pei, Y. Zhang, S. Zhang, and J. Yu, "An indoor localization method based on aoa and pdoa using virtual stations in multipath and nlos environments for passive uhf rfid," in *IEEE Access*, 2018.

[65] L. Mo, Y. Zhu, and D. Zhang, "Uhf rfid indoor localization algorithm based on bp-svr," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 385–393, 2022.

[66] P. V. Nikitin, R. Martinez, S. Ramamurthy, H. Leland, G. Spiess, and K. V. S. Rao, "Phase based spatial identification of uhf rfid tags," in *2010 IEEE International Conference on RFID (IEEE RFID 2010)*, 2010, pp. 102–109.

[67] A. Povalac and J. Sebesta, "Phase difference of arrival distance estimation for rfid tags in frequency domain," in *2011 IEEE International Conference on RFID-Technologies and Applications*, 2011, pp. 188–193.

[68] R. Miesen, F. Kirsch, and M. Vossiek, "Uhf rfid localization based on synthetic apertures," *IEEE Transactions on Automation Science and Engineering*, vol. 10, pp. 807–815, 2013.

[69] E. DiGiampaolo and F. Martinelli, "Mobile robot localization using the phase of passive uhf rfid signals," *IEEE Transactions on Industrial Electronics*, vol. 61, pp. 365–376, 2014.

[70] A. Buffi, P. Nepa, and F. Lombardini, "A phase-based technique for localization of uhf-rfid tags moving on a conveyor belt: Performance analysis and test-case measurements," *IEEE Sensors Journal*, vol. 15, no. 1, pp. 387–396, 2015.

[71] A. Buffi and P. Nepa, "The sarfid technique for discriminating tagged items moving through a uhf-rfid gate," *IEEE Sensors Journal*, vol. 17, no. 9, pp. 2863–2870, 2017.

[72] X. Li, Y. Zhang, and M. G. Amin, "Multifrequency-based range estimation of rfid tags," in *2009 IEEE International Conference on RFID*, 2009, pp. 147–154.

[73] S. Kunkel, R. Bieber, M.-S. Huang, and M. Vossiek, "A concept for infrastructure independent localization and augmented reality visualization of rfid tags," in *2009 IEEE MTT-S International Microwave Workshop on Wireless Sensing, Local Positioning, and RFID*, 2009, pp. 1–4.

[74] S. Sarkka, V. V. Viikari, M. Huusko, and K. Jaakkola, "Phase-based uhf rfid tracking with nonlinear kalman filtering and smoothing," *IEEE Sensors Journal*, vol. 12, no. 5, pp. 904–910, 2012.

[75] F. Zafari, A. Gkelias, and K. K. Leung, "A survey of indoor localization systems and technologies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2568–2599, 2019.

[76] H. Ma and K. Wang, "Fusion of rss and phase shift using the kalman filter for rfid tracking," *IEEE Sensors Journal*, vol. 17, no. 11, pp. 3551–3558, 2017.

[77] R. Miyamoto, K. M. K. H. Leong, S.-S. Jeon, and Y. Wang, "Location of mobile terminals using time measurements and survey points," *IEEE Transactions on Vehicular Technology*, vol. 52, no. 4, pp. 999–1011, 2003.

[78] X. Zhu, W. Qu, T. Qiu, L. Zhao, M. Atiquzzaman, and D. O. Wu, "Indoor intelligent fingerprint-based localization: Principles, approaches and challenges," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2634–2657, 2020.

[79] C. Nerguizian, C. L. Despins, and S. Affes, "Geolocation in mines with an impulse response fingerprinting technique and neural networks," *IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall. 2004*, vol. 5, pp. 3589–3594 Vol. 5, 2004.

[80] E. L. Berz, D. A. Tesch, and F. P. Hessel, "Machine-learning-based system for multi-sensor 3d localisation of stationary objects," *IET Cyber-Physical Systems: Theory & Applications*, vol. 3, no. 2, pp. 81–88, 2018.

[81] M. Altini, D. Brunelli, E. Farella, and L. Benini, "Bluetooth indoor localization with multiple neural networks," in *IEEE 5th International Symposium on Wireless Pervasive Computing 2010*, 2010, pp. 295–300.

[82] K. Yamano, K. Tanaka, M. Hirayama, E. Kondo, Y. Kimuro, and M. Matsumoto, "Self-localization of mobile robots with rfid system by using support vector machine," in *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566)*, vol. 4, 2004, pp. 3756–3761 vol.4.

[83] A. Wille, M. Broll, and S. Winter, "Phase difference based rfid navigation for medical applications," *2011 IEEE International Conference on RFID*, pp. 98–105, 2011.

[84] B. E. Boser, I. M. Guyon, and V. N. Vapnik, "A training algorithm for optimal margin classifiers," in *Annual Conference Computational Learning Theory*, 1992.

[85] A. M. Sazdar, S. A. Ghorashi, V. Moghtadaiee, A. Khonsari, and D. Windridge, "A low-complexity trajectory privacy preservation approach for indoor fingerprinting positioning systems," *Journal of Information Security and Applications*, vol. 53, p. 102515, 2020.

[86] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, pp. 1067–1080, 2007.

[87] L. Ni, Y. Liu, Y. C. Lau, and A. Patil, "Landmarc: indoor location sensing using active rfid," in *Proceedings of the First IEEE International Conference on Pervasive Computing and Communications, 2003. (PerCom 2003).*, 2003, pp. 407–415.

[88] Z. Belhadi and L. Fergani, "Fingerprinting methods for rfid tag indoor localization," in *2014 International Conference on Multimedia Computing and Systems (ICMCS)*, 2014, pp. 717–722.

[89] B. Wagner, N. Patwari, and D. Timmermann, "Passive rfid tomographic imaging for device-free user localization," *2012 9th Workshop on Positioning, Navigation and Communication*, pp. 120–125, 2012.

[90] L. Yang, Y. Chen, X. Li, C. Xiao, M. Li, and Y. Liu, "Tagoram: Real-time tracking of mobile rfid tags to high precision using cots devices," in *MobiCom 2014 - Proceedings of the 20th Annual*. Association for Computing Machinery, Jan. 2014, pp. 237–248, 20th ACM Annual International Conference on Mobile Computing and Networking, MobiCom 2014 ; Conference date: 07-09-2014 Through 11-09-2014.

[91] M. Bolic, M. Rostamian, and P. M. Djuric, "Proximity detection with rfid: A step toward the internet of things," *IEEE Pervasive Computing*, vol. 14, pp. 70–76, 2015.

[92] C. Laoudias, A. Moreira, S. Kim, S. Lee, L. Wirola, and C. Fischione, "A survey of enabling technologies for network localization, tracking, and navigation," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3607–3644, 2018.

[93] A. Tahat, G. Kaddoum, S. Yousefi, S. Valaee, and F. Gagnon, "A look at the recent wireless positioning techniques with a focus on algorithms for moving receivers," *IEEE Access*, vol. 4, pp. 6652–6680, 2016.

[94] M. B. Alatise and G. P. Hancke, "A review on challenges of autonomous mobile robot and sensor fusion methods," *IEEE Access*, vol. 8, pp. 39 830–39 846, 2020.

[95] F. Alam, N. Faulkner, and B. Parr, "Device-free localization: A review of non-rf techniques for unobtrusive indoor positioning," *IEEE Internet of Things Journal*, vol. 8, no. 6, pp. 4228–4249, 2021.

[96] X. Guo, N. Ansari, F. Hu, Y. Shao, N. R. Elikplim, and L. Li, "A survey on fusion-based indoor positioning," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 566–594, 2020.

[97] T. Gaedeke, M. Johnson, M. Hedley, and W. Stork, "Fusion of wireless ranging and inertial sensors for precise and scalable indoor localization," in *2014 IEEE International Conference on Communications Workshops (ICC)*, 2014, pp. 138–143.

[98] A. Colombo, D. Fontanelli, D. Macii, and L. Palopoli, "Flexible indoor localization and tracking based on a wearable platform and sensor data fusion," *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 4, pp. 864–876, 2014.

[99] J. Orlosky, T. Toyama, D. Sonntag, A. Sarkany, and A. Lorincz, "On-body multi-input indoor localization for dynamic emergency scenarios: fusion of magnetic tracking and optical character recognition with mixed-reality display," in *2014 IEEE International Conference on Pervasive Computing and Communication Workshops (PERCOM WORKSHOPS)*, 2014, pp. 320–325.

[100] B. Xu and W. Gang, "Random sampling algorithm in rfid indoor location system," in *Third IEEE International Workshop on Electronic Design, Test and Applications (DELTA'06)*, 2006, pp. 6 pp.–176.

[101] T. Sanpechuda and L. Kovavisaruch, "A review of rfid localization: Applications and techniques," in *2008 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, vol. 2, 2008, pp. 769–772.

[102] R. Almomani, M. Dong, and D. Zhu, "A bayesian hierarchical appearance model for robust object tracking," in *2016 IEEE International Conference on Multimedia and Expo (ICME)*, 2016, pp. 1–6.

[103] N. G. Ferrara, H. Wymeersch, E. S. Lohan, and J. Nurmi, "A comparison of bayesian localization methods in the presence of outliers," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2017, pp. 1546–1551.

[104] A. Krishna and C. S. Thakur, "Bayesian source localization using stochastic computation," in *2021 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2021, pp. i–5.

[105] G. Welch and G. Bishop, "Welch & bishop , an introduction to the kalman filter 2 1 the discrete kalman filter in 1960," 1994.

[106] F. Gustafsson, F. Gunnarsson, N. Bergman, U. Forssell, J. Jansson, R. Karlsson, and P. J. Nordlund, "Particle filters for positioning, navigation, and tracking," *IEEE Transactions on Signal Processing*, vol. 50, no. 2, pp. 425–437, 2002.

[107] Z. Xiong, Z. Y. Song, A. Scalera, E. Ferrera, F. Sottile, P. Brizzi, R. Tomasi, and M. A. Spirito, "Hybrid wsn and rfid indoor positioning and tracking system," *EURASIP Journal on Embedded Systems*, vol. 2013, pp. 1–15, 2013.

[108] S. Subedi, E. Pauls, and Y. D. Zhang, "Accurate localization and tracking of a passive rfid reader based on rssi measurements," *IEEE Journal of Radio Frequency Identification*, vol. 1, no. 2, pp. 144–154, 2017.

[109] K. Chen, Y. Ma, H. Liu, X. Liang, and Y. Fu, "Trajectory-robust rfid relative localization based on phase profile correlation," *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1–13, 2023.

[110] A. R. Chatzistefanou, G. Sergiadis, and A. G. Dimitriou, "Tag localization by handheld uhf rfid reader with optical and rfid landmarks," *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 330–340, 2023.

[111] H. Ding, J. Han, C. Qian, F. Xiao, G. Wang, N. Yang, W. Xi, and J. Xiao, "Trio: Utilizing tag interference for refined localization of passive rfid," in *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, 2018, pp. 828–836.

[112] H. Fu, Y. Ma, X. Gong, X. Zhang, B. Wang, W. Ning, and X. Liang, "Device-free multitarget localization with weighted intersection multidimensional feature for passive uhf rfid," *IEEE Sensors Journal*, vol. 22, no. 7, pp. 7300–7310, 2022.

[113] Y. Ma, C. Tian, and H. Liu, "Muse: A multistage assembling algorithm for simultaneous localization of large-scale massive passive rfids," *IEEE Transactions on Mobile Computing*, vol. 21, no. 5, pp. 1766–1778, 2022.

[114] C. Yang, X. Wang, and S. Mao, "Rfid tag localization with a sparse tag array," *IEEE Internet of Things Journal*, vol. 9, no. 18, pp. 16 976–16 989, 2022.

[115] L. Gui, S. Xu, F. Xiao, F. Shu, and S. Yu, "Non-line-of-sight localization of passive uhf rfid tags in smart storage systems," *IEEE Transactions on Mobile Computing*, vol. 21, no. 10, pp. 3731–3743, 2022.

[116] A. R. Chatzistefanou, S. Megalou, S. Siachalou, V. Drakaki, G. D. Sergiadis, and A. G. Dimitriou, "Target localization by mobile handheld uhf rfid reader," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*, 2022, pp. 1–5.

[117] W. Shi, Z. Chen, K. Zhao, W. Xi, Y. Qu, H. He, Z. Guo, Z. Ma, X. Huang, P. Wang, B. Dong, and J. Zhao, "3d target location based on rfid polarization phase model," *EURASIP Journal on Wireless Communications and Networking*, vol. 17, March 2022.

[118] Z. Xiong, F. Sottile, M. A. Spirito, and R. Garello, "Hybrid indoor positioning approaches based on wsn and rfid," in *2011 4th IFIP International Conference on New Technologies, Mobility and Security*, 2011, pp. 1–5.

[119] Z. Xiong, F. Sottile, A. Caceres, M. A. Spirito, and P. Brizzi, "Hybrid wsn-rfid cooperative positioning based on extended kalman filter," in *2011 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications*, 2011, pp. 990–993.

[120] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[121] P. Tripicchio, M. Unetti, S. D'Avella, A. Buffi, A. Motroni, F. Bernardini, and P. Nepa, "A synthetic aperture uhf rfid localization method by phase unwrapping and hyperbolic intersection," *IEEE Transactions on Automation Science and Engineering*, vol. 19, no. 2, pp. 933–945, 2022.

[122] C. Wu, Z. Gong, B. Tao, K. Tan, Z. Gu, and Z.-P. Yin, "Rf-slam: Uhf-rfid based simultaneous tags mapping and robot localization algorithm for smart warehouse position service," *IEEE Transactions on Industrial Informatics*, vol. 19, no. 12, pp. 11 765–11 775, 2023.

[123] E. D. Giampaolo, F. Martinelli, and F. Romanelli, "Robust simultaneous localization and mapping using the relative pose estimation of trilateration uhf rfid tags," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 583–592, 2022.

[124] F. Martinelli, "Simultaneous localization and mapping using the phase of passive uhf-rfid signals," *Journal of Intelligent & Robotic Systems*, vol. 94, p. 711–725, July 2019.

[125] A. Aguilar-Garcia, S. Fortes, E. Colin, and R. Barco, "Enhancing rfid indoor localization with cellular technologies," *EURASIP Journal on Wireless Communications and Networking*, 2015.

[126] G. T. Hao Wu, Xiaojian Wu, "Indoor robot localization based on single rfid tag," *Artificial Life and Robotics*, vol. 23, p. 373–379, July 2018.

[127] A. Vena, I. Illanes, L. Alidieres, B. Sorli, and F. Perea, "Rfid based indoor localization system to analyze visitor behavior in a museum," in *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2021, pp. 183–186.

[128] R. Miesen, F. Kirsch, and M. Vossiek, "Holographic localization of passive uhf rfid transponders," in *2011 IEEE International Conference on RFID*, 2011, pp. 32–37.

[129] M. El-Absi, A. Al-Haj Abbas, and T. Kaiser, "Chipless rfid tags placement optimization as infrastructure for maximal localization coverage," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 368–380, 2022.

[130] A. R. Dastkhosh, M. Naseh, and F. Lin, "K/ka slotted stacked patch antenna and active array antenna design for a 5g/6g satellite mobile communication system," in *2021 13th Global Symposium on Millimeter-Waves & Terahertz (GSMM)*, 2021, pp. 1–3.

[131] A. R. Dastkhosh, Z.-X. Zhang, M. Naseh, V. Moeyaert, and F. Lin, "K/ka-band compact low-profile dual differential-fed split ring resonator magnetic-dipole antenna with uwb-frequency-tuning and broad scanning capabilities," *Results in Engineering*, vol. 27, p. 106649, 2025.

[132] A. R. Dastkhosh, A. Mehbodniya, J. Webber, M. Naseh, M. Dadras Jedi, and F. Lin, "Small dual polarized uwb antenna

and its array analysis for 5g/6g applications," *Emerging Science Journal*, vol. 9, no. 6, p. 2929–2945, Dec. 2025.

[133] A. Lazaro, A. Ramos, R. Villarino, and D. Girbau, "Active uwb reflector for rfid and wireless sensor networks," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4767–4774, 2013.

[134] M. Baghaei-Nejad, D. S. Mendoza, Z. Zou, S. Radiom, G. Gielen, L.-R. Zheng, and H. Tenhunen, "A remote-powered rfid tag with 10mb/s uwb uplink and -18.5dbm sensitivity uhf downlink in 0.18μm cmos," in *2009 IEEE International Solid-State Circuits Conference - Digest of Technical Papers*, 2009, pp. 198–199.

[135] N. Decarli, A. Guerra, F. Guidi, M. Chiani, D. Dardari, A. Costanzo, M. Fantuzzi, D. Masotti, S. Bartoletti, J. S. Dehkordi, A. Conti, A. Romani, M. Tartagni, R. Alesii, P. Di Marco, F. Santucci, L. Roselli, M. Virili, P. Savazzi, and M. Bozzi, "The greta architecture for energy efficient radio identification and localization," in *2015 International EURASIP Workshop on RFID Technology (EURFID)*, 2015, pp. 1–8.

[136] M. Z. Win, D. Dardari, A. F. Molisch, W. Wiesbeck, and J. Zhang, "History and applications of uwb [scanning the issue]," *Proceedings of the IEEE*, vol. 97, no. 2, pp. 198–204, 2009.

[137] F. C. Commission, "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," Tech. Rep., 2022.

[138] "Ieee standard for local and metropolitan area networks– part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 2: Active radio frequency identification (rfid) system physical layer (phy)," *IEEE Std 802.15.4f-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–72, 2012.

[139] A. R. Dastkhosh, M. Naseh, D. Dardari, and F. Lin, "Tv-based phased array system design in btss for 5g/iot applications," *Progress In Electromagnetics Research C*, vol. 127, pp. 1–16, 2022.

[140] H. R. D. Oskouei, A. R. Dastkhosh, A. Mirtaheri, and M. Naseh, "A small cost-effective super ultra-wideband microstrip antenna with variable band-notch filtering and improved radiation pattern with 5g/iot applications," *Progress In Electromagnetics Research M*, vol. 83, pp. 191–202, 2019.

[141] A. Guerra, N. Decarli, F. Guidi, and D. Dardari, "Energy sprinklers for passive uwb rfid," in *2014 IEEE International Conference on Ultra-WideBand (ICUWB)*, 2014, pp. 356–361.

[142] H. Wymeersch, G. Seco-Granados, G. Destino, D. Dardari, and F. Tufvesson, "5g mmwave positioning for vehicular networks," *IEEE Wireless Communications*, vol. 24, no. 6, pp. 80–86, 2017.

[143] A. R. Dastkhosh, Z. Khan, M. Naseh, and F. Lin, "Link budget calculations for k/ka-band satellite mobile communication systems," in *2022 IEEE MTT-S International Wireless Symposium (IWS)*, vol. 1, 2022, pp. 1–3.

[144] E. Soltanaghaei, A. Prabhakara, A. Balanuta, M. Anderson, J. M. Rabaey, S. Kumar, and A. Rowe, "Millimetro: mmwave retro-reflective tags for accurate, long range localization," in *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '21. New York, NY, USA: Association for Computing Machinery, 2021, p. 69–82.

[145] J. G. Hester and M. M. Tentzeris, "A mm-wave ultra-long-range energy-autonomous printed rfid-enabled van-atta wireless sensor: At the crossroads of 5g and iot," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, 2017, pp. 1557–1560.

[146] D. Dardari, M. Lotti, N. Decarli, and G. Pasolini, "Grant-free random access with backscattering self-conjugating metasurfaces," *IEEE Transactions on Cognitive Communications and Networking*, vol. 10, no. 5, pp. 1620–1634, 2024.

[147] ——, "Establishing multi-user mimo communications automatically using retrodirective arrays," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1396–1416, 2023.

[148] L. Xie, C. Wang, Y. Bu, J. Sun, Q. Cai, J. Wu, and S. Lu, "Taggedar: An rfid-based approach for recognition of multiple tagged objects in augmented reality systems," *IEEE Transactions on Mobile Computing*, vol. 18, no. 5, pp. 1188–1202, 2019.

[149] L. Kubáč, V. Kebo, F. Beneš, and P. Staša, "Rfid and augmented reality," in *Proceedings of the 14th International Carpathian Control Conference (ICCC)*, 2013, pp. 186–191.

[150] T. Boroushaki, M. Lam, W. Chen, L. Dodds, A. Eid, and F. Adib, "Exploiting synergies between augmented reality and rfids for item localization and retrieval," in *2023 IEEE International Conference on RFID (RFID)*, 2023, pp. 30–35.

[151] R. Xiao, A. Vianto, A. Shaikh, O. Buruk, J. Hamari, and J. Virkki, "Exploring the application of rfid for designing augmented virtual reality experience," *IEEE Access*, vol. 10, pp. 96 840–96 851, 2022.

[152] T. W. Callis, M. Joshi, and M. M. Tentzeris, "Novel mmwave/5g rfid architectures for next generation of iot devices and vr applications," in *2024 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2024, pp. 101–104.

[153] B. Durtschi, M. M. Fouda, and A. Chrysler, "Ai-driven error correction for knn-based rfid localization," in *2024 IEEE International Conference on Internet of Things and Intelligence Systems (IoTaIS)*, 2024, pp. 172–176.

[154] M. Merenda, L. Catarinucci, R. Colella, D. Iero, F. G. D. Corte, and R. Carotenuto, "Rfid-based indoor positioning using edge machine learning," *IEEE Journal of Radio Frequency Identification*, vol. 6, pp. 573–582, 2022.

[155] M. I. Zulfiqar, A. Khalid, A. Siddig, M. J. Nawaz, and S. Saay, "Ai-driven smart shopping carts with real-time tracking and inventory forecasting for enhanced retail efficiency," *IEEE Access*, vol. 13, pp. 55 576–55 585, 2025.

[156] R. Kanjilal, M. Furkan Kucuk, and I. Uysal, "Human activity recognition: A review of rfid and wearable sensor technologies powered by ai," *IEEE Journal of Radio Frequency Identification*, vol. 9, pp. 180–199, 2025.

[157] H. Zhang and Z. Li, "Rfid supply chain data deconstruction method based on artificial intelligence technology," *Open Computer Science*, vol. 13, no. 1, p. 20220265, 2023.

[158] Y. Xu, Z. Li, Z. Zhao, B. H. Aguenoukoun, J. Liu, Z. Chang, and Y. Liu, "Machine learning enhanced indoor positioning with ris-aided channel configuration and analysis," in *2024 IEEE 23rd International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*, 2024, pp. 2653–2660.

[159] D. Dardari, N. Decarli, A. Guerra, and F. Guidi, "Los/nlos near-field localization with a large reconfigurable intelligent surface," *IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 4282–4294, 2022.

[160] J. Tong, X. Zhao, Z. Wang, D. Dai, Z. An, and L. Yang, "Commercial rfids as reconfigurable intelligent surfaces," in *IEEE INFOCOM 2025 - IEEE Conference on Computer Communications*, 2025, pp. 1–10.

[161] M. El-Absi, A. A. Abbas, D. Tubail, F. Ilgac, A. Abuelhaija, Y. Zantah, S. Ikki, A. Sezgin, and T. Kaiser, "Path loss modeling of rfid backscatter channels with reconfigurable intelligent surface: Experimental validation," *IEEE Access*, vol. 11, pp. 108 532–108 543, 2023.

[162] C. Li, Q. Huang, Y. Zhou, Y. Huang, Q. Hu, H. Chen, and Q. Zhang, "Riscan: Ris-aided multi-user indoor localization using cots wi-fi," in *Proceedings of the 21st ACM Conference on Embedded Networked Sensor Systems*, ser. SenSys '23. New York, NY, USA: Association for Computing Machinery, 2024, p. 445–458.

[163] Z. Lu, Y. Zhao, X. Li, and C.-Z. Xu, "Randomized passive energy beamforming for cooperative localization in reconfigurable intelligent surface-assisted wireless backscattered sensor network," *IEEE Internet of Things Journal*, vol. 11, no. 6, pp. 9693–9707, 2024.

[164] J. Ma, X. Wang, C. Powell, J. Zhang, S. Mao, S. C. Periaswamy, and J. Patton, "Digital twin of retail stores with rfid tags localization," in *2024 9th International Conference on Smart and Sustainable Technologies (SpliTech)*, 2024, pp. 01–06.

[165] C. Turner, D. Bhaskaruni, X. Wang, J. Zhang, S. Mao, S. C. Periaswamy, and J. Patton, "Digital twin of retail environment using rfid particle filter localization," in *2025 10th International Conference on Smart and Sustainable Technologies (SpliTech)*, 2025, pp. 1–6.

[166] R. Pous, M. Chindemi, and A. Alajami, "Showing products in a retail store digital twin with item location captured by an rfid robot," in *2023 IEEE 13th International Conference on RFID Technology and Applications (RFID-TA)*, 2023, pp. 189–192.

[167] J. Wittmann, C. Huber, L. Rissmann, and S. Meissner, "3d-localization of rfid tags for a digital twin of an industrial order-picking process," in *2024 International Conference on Control, Automation and Diagnosis (ICCAD)*, 2024, pp. 1–6.