An Overview of Antenna Designs for Indoor Positioning Systems in Industry 4.0

Zayed Nasser
WiSAR Lab
Atlantic Technological University,
Letterkenny, Ireland
L00194465@atu.ie

Tale Saeidi
WiSAR Lab
Atlantic Technological University, Letterkenny, Ireland
Tale.saeidi@atu.ie

Sahar Saleh
WiSAR Lab
Atlantic Technological University, Letterkenny, Ireland
University of Aden, Aden, Yemen
sahar.saleh@atu.ie, sahar.abdulrazzaq.eng@aden-univ.net

Nick Timmons
WiSAR Lab, Atlantic Technological University, Letterkenny, Ireland
nick.timmons@atu.ie

Intan Sorfina Zainal Abidin
Universiti Sains Malaysia
Penang, Malaysia
intan.sorfina@usm.my

Shahanawaz Kamal
Radio Frequency Design Enablement Group, Barkhausen Institut, Dresden, Germany
shahanawaz.kamal@barkhauseninstitut.org

Abstract— **Indoor Positioning Systems (IPS) constitute a vital component of industrial environments, enabling real-time tracking of assets, workflows, and personnel. The effectiveness of these systems is closely tied to antenna design, which governs signal propagation and the precision of position estimation in complex factory settings. This paper presents an overview of antenna design considerations for industrial IPS. It examines the role of antennas in achieving reliable operation, outlines the primary challenges of designing antennas for indoor industrial environments, surveys current antenna solutions, and identifies areas where further research is likely to yield advancements.**

Keywords—Indoor positioning, antenna design, Industry 4.0, IPS

I. INTRODUCTION

The emergence of Industry 4.0 has advanced automation, flexibility, and operational efficiency across industrial sectors. Central to this transformation is the demand for accurate real-time location data of assets within operational environments such as smart factories and warehouses. Precise tracking of objects, automated guided vehicles (AGVs), and personnel supports critical functions, including autonomous navigation, inventory optimization, and safety enforcement [1], [2].

In the Asia-Pacific region, national initiatives increasingly prioritize Industry 4.0 implementation. For example, Malaysia's industrial strategies emphasize the development of smart factories through the integration of automation, robotics, and IoT-based systems to enhance manufacturing competitiveness and safety. This strategic focus has intensified the demand for scalable solutions dependent on robust spatial awareness [3] [4]. Consequently, IPS have become integral to realizing these capabilities. However, industrial environments characterized by metallic structures, heavy machinery, and dynamic workflows present distinct radio frequency propagation challenges. Signal degradation arises from multipath reflection, absorption, diffraction, and

attenuation. Physical obstructions often induce non-line-of-sight (NLOS) conditions that compromise transmission reliability. To sustain positioning accuracy in such contexts, antenna designs must be optimized to mitigate environmental effects. Essential design objectives include resilience to multipath interference, suppression of electromagnetic interference (EMI), and directional control to reduce obstruction-related degradation.

Antennas are fundamental to wireless communication systems, and their function assumes particular significance in Industrial Indoor Positioning Systems (IPS), where they enable signal acquisition and support the estimation of relative device positions based on parameters such as signal strength and time of arrival. In industrial environments, where signal propagation is often hindered by complex architectural layouts, metallic infrastructure, machinery, and continuous human presence, antennas operate not merely as passive transducers but as active elements that can either alleviate or intensify these constraints [5]. Their influence on signal coverage, mitigation of multipath fading, and resistance to electromagnetic interference (EMI) is critical for sustaining consistent and precise positioning performance. The overall capability of an IPS to deliver accuracy, reliability, and resilience is closely linked to the properties and deployment strategies of the antennas selected [6]. Depending on operational requirements, configurations may be directional, providing enhanced precision for targeted localization, or omnidirectional, offering broader coverage and adaptability in dynamic industrial settings [7]. Careful selection, design, and integration of antennas are therefore essential for achieving the high-fidelity, real-time location data required in Industry 4.0 applications, including asset tracking, autonomous guided vehicle navigation, collaborative robotics, and process optimization, all of which depend on robust and precise positioning systems tailored to the complexities of contemporary manufacturing and logistics.

This review offers an overview of antenna designs for IPS in Industry 4.0 applications. It discusses key challenges and requirements, relevant antenna technologies, critical design considerations, and emerging trends.

The paper is organized as follows: Section I presents the background and context. Section II analyses design challenges associated with IPS deployment. Section III

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explores antenna applications in IPS. Section V examines antenna designs and configurations for industrial environments. Section VI concludes with implications for the development of reliable IPS solutions.

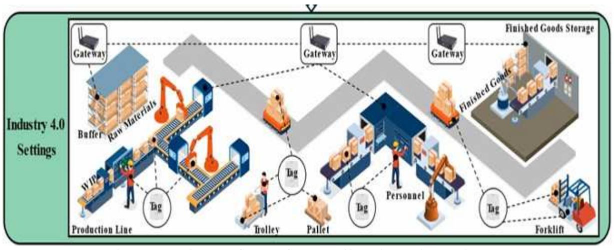

Figure 1. The overview of IPS for applications in Industry 4.0.[1].

II. CHALLENGES OF ANTENNA DESIGN IN INDUSTRIAL IPS

The cluttered nature of industrial settings—dominated by metal frameworks, machinery, and dynamic equipment—creates challenging radio propagation conditions. These factors contribute to complex and dynamic propagation conditions. Multipath effects are a primary concern, as signals reflect, diffract, and scatter off surfaces, creating multiple paths between transmitter and receiver. This behaviour results in signal fading, phase distortion, and measurement errors that reduce localization accuracy [8] . Antennas deployed under these conditions must exhibit strong multipath resolution capability. This can be achieved through wide bandwidth, as in ultra-wideband (UWB) systems, or through advanced signal processing techniques combined with antenna arrays. EMI represents an additional challenge. Industrial facilities house numerous machines and electrical devices that generate considerable EMI, disrupting transmissions and reducing signal-to-noise ratios. Antennas must maintain robust performance through filtering, shielding, or specific polarization characteristics. The crowded sub-6 GHz ISM bands used by Wi-Fi and other systems further complicate coexistence and increase the likelihood of interference [9]. Such environments often result in obstructed signals and prevalent non-line-of-sight (NLOS) conditions, especially near large machinery or stacked goods. These obstacles frequently attenuate signals and degrade position estimates [10] . Antennas capable of maintaining performance under NLOS conditions, whether through pattern diversity or utilization of reflected paths, are of value. Furthermore, the dynamic nature of industrial environments, including moving equipment such as automated guided vehicles (AGVs) and frequently reconfigured layouts, means that the radio channel conditions are rarely static, requiring antennas and positioning systems to adapt to temporal variations [11] . Material interactions further complicate signal behaviour, as metallic surfaces often cause pronounced reflections, while certain materials absorb electromagnetic energy, reducing signal strength and coverage. Antenna orientation, in both fixed installations and mobile tags, strongly affects performance, particularly in directional configurations or those relying on specific polarization. Addressing these challenges requires precise antenna selection, strategic placement, and, in many cases, sophisticated signal processing to compensate for adverse propagation effects. Together, these measures are essential to achieving reliable and accurate indoor positioning.

III. ANTENNA APPLICATIONS IN INDUSTRIAL IPS

The deployment of antennas in industrial IPS is inherently application-specific, as each use case imposes distinct operational requirements. For example, for asset tracking, where the objective is to monitor the location of tools, inventory, and equipment, antennas must provide consistent coverage across the facility, including within shelving units and enclosed machinery [12]. Compact and economical designs are integrated into asset tags that operate on limited battery capacity, necessitating high efficiency under constrained power budgets. In extensive warehouses or open production areas, a combination of omnidirectional antennas on tags and strategically placed directional antennas at fixed anchors can enhance coverage and improve localization accuracy. In the context of Autonomous Guided Vehicle (AGV) navigation, precise and continuous positioning is essential to ensure safe and reliable operation. AGVs typically employ antennas that support both communication and localization, with directional elements or beamforming arrays used to maintain robust links to infrastructure and to determine the vehicle's position and orientation, particularly in dynamic environments populated by other moving equipment [13]. It is common to integrate multiple antenna types on a single AGV platform, combining ultra-wideband (UWB) antennas for fine-grained positioning with Wi-Fi or 5G antennas for data exchange. Personnel safety applications, such as monitoring workers in hazardous zones or maintaining safe separation from automated machinery, demand highly dependable and often wearable IPS solutions. Antennas incorporated into wearable tags must be compact and lightweight while delivering stable performance when mounted on the human body, which can detune the antenna and absorb radiated energy. Textile antennas and flexible substrates are increasingly adopted for this purpose, while anchor nodes supporting these systems must be installed to ensure uninterrupted coverage in high-risk areas [14]. For applications involving real-time monitoring of industrial processes and equipment, antennas may be embedded within enclosures or distributed throughout sensor networks, requiring mechanical robustness to withstand vibrations, fluctuations, and other operational stresses while maintaining consistent data transmission for sensing and positioning. In all scenarios, rigorous assessment of antenna placement, orientation, and interaction with the surrounding environment is essential to ensure the intended system performance. The choice of antenna architecture, radiation properties, and integration methods must be closely aligned with the functional requirements and environmental conditions of each application.

IV. ANTENNA DESIGNS AND CONFIGURATIONS FOR INDUSTRIAL IPS

The propagation of electromagnetic (EM) waves plays a central role in designing antennas that can function reliably within the complex indoor environment's characteristic of industrial settings. Addressing the specific propagation challenges in these settings—such as reflection, diffraction, and scattering caused by dense machinery and structural materials—is essential for developing antenna solutions that provide consistent and accurate positioning data. The performance of IPS depends heavily on the properties of the antennas used, including their gain, bandwidth, beam-steering capability, and physical size. These characteristics directly influence signal coverage and determine the accuracy of positioning in industrial environments.

To support highly accurate and low-cost two-dimensional direction-of-arrival (DoA) estimation in IoT networks without the need for active scanning circuits, passive frequency-scanned leaky-wave antenna (LWA) designs have been developed for use within the Bluetooth Low Energy (BLE) advertising band (2.402–2.48 GHz) [15]. By varying their operating frequency, LWAs can steer their beams continuously, making them particularly well suited to applications that demand dynamic coverage or reliable tracking of moving targets. Several strategies have been introduced to improve their performance. For instance, a passive monopulse LWA system developed in [16] combines a bidirectionally fed planar structure with amplitude-monopulse processing of received signal strength measurements to estimate angles of arrival in Wi-Fi networks. This approach demonstrated accuracy comparable to, and in some cases exceeding, that of tilted array configurations at short distances, while eliminating the need for active circuitry or phase measurements. Similarly, [17] presented a frequency-steered LWA array capable of forming twelve narrow beams aligned with BLE advertising channels. This design achieved departure angle estimation errors of approximately 3.7° across a 120° field of view using only passive RSSI-based processing.

Multiple-input multiple-output (MIMO) antenna systems critically enhance both communication capacity and localization accuracy within industrial IPS [18]. By leveraging multipath propagation, MIMO configurations increase data throughput, offer greater spatial diversity, and significantly improve positioning precision. Furthermore, MIMO systems provide richer channel state information (CSI). This enhanced CSI enables robust fingerprint-based localization and improves the reliability of geometric parameter estimation, notably Angle of Arrival (AoA) and Time of Arrival (ToA). For precise positioning on UWB Channel 9, a low-profile, three-element circularly polarized (CP) MIMO antenna was designed in [19]. The three elements are strategically arranged to form a MIMO system that enhances spatial coverage and reduces spatial correlation, which is crucial for accurate localization. The system demonstrates excellent performance, with high port isolation (>22.5 dB), wide bandwidth, and stable gain, ultimately enabling more accurate and computationally efficient indoor positioning compared to existing methods. In [20], a compact multimode MIMO antenna developed for AoA estimation in space-limited IoT devices achieved a full 360° field of view with angular errors under 0.1°. This design reduced antenna size by nearly 35% compared to conventional arrays while preserving the ability to distinguish multiple simultaneous signals, making it a practical solution for high-precision localization in confined environments.

Microstrip patch antennas have become popular in IoT applications for indoor positioning systems in industrial environments, owing to their compact form factor, ease of integration, and predictable radiation characteristics [21] . The planar geometry of patch antennas makes them particularly well suited for integration into industrial IoT devices and positioning tags, where space constraints and mechanical durability are critical considerations. Recent developments in patch antenna design for industrial applications have focused on achieving broad bandwidth operation to support multiple positioning techniques simultaneously, including ultra-wideband (UWB) ranging [8]. Circular polarization capability has also become increasingly important, as it improves performance in multipath environments and reduces the influence of antenna orientation on positioning accuracy [22]. In indoor localization, omnidirectional antennas provide uniform coverage, reduce blind spots, and support reliable signal reception from multiple angles, making them well-suited for dynamic environments with unpredictable tag movement [23]. However, their lack of spatial selectivity limits angular resolution. In contrast, directional antennas improve positioning accuracy by concentrating energy in specific directions, thereby reducing multipath interference and enabling high-resolution angle estimation—capabilities that are crucial for precise localization in indoor industrial environments [24].

Table 1 . Comparison of Antennas Used in IPS.

Ref.	Antenna type	Gain (dbi)	Size (λ_o)	Multipath Resilience	EMI Tolerance
[15]	SIW LWA	3	4.2	Good	Moderate
[25]	Microstrip LWA	3–6	1.7	Good	Moderate
[17]	LWA array	2–4	1.1	High	Moderate
[19]	MIMO patch	5.4–8.1	0.6	High	High (CP)
[22]	Microstrip array	0.8–1.2	0.76	High	High
[26]	Switched circular array	6.6	0.13	Moderate	Moderate
[27]	Element switched CP array	7.6–9.8	0.9	High	Moderate

Reconfigurable antennas represent another significant advance, enabling dynamic adjustment of operating frequency, radiation pattern, or polarization to adapt to changing environmental conditions and system requirements [28]. For example, [26] introduced a switched-beam circular array combining a dielectric superstrate with an RF MEMS switching network to achieve full 360° azimuth coverage. This system supported direction and distance estimation with errors between 0.15 and 0.34 meters at a 2-meter range. In [27] , a circularly polarized smart antenna that electronically reconfigures its beam by selecting among seven high-gain elements, each covering a different sector, is presented. This approach enabled a single anchor node to provide complete area coverage with a mean localization error of 0.72 meters, reducing the complexity and cost of deploying multiple anchor points. The adaptability of such reconfigurable antennas makes them especially well suited to the dynamic radio environments typical of industrial settings, supporting more reliable and precise indoor positioning.

V. CONCLUSION AND FUTURE DIRECTIONS

Antenna Antenna design plays a key role in ensuring accurate and reliable indoor positioning systems (IPS) in industrial settings. Despite progress, challenges like signal reflections, EMI, and mechanical limitations still impact performance. As industries move toward greater connectivity and automation, antennas must become more adaptable, efficient, and resilient to meet evolving demands.

Future research will likely focus on millimeter-wave antennas for high-precision tracking, hybrid beamforming for better directionality and interference reduction, and the integration of machine learning to enable smart, adaptive antenna systems. Advancing these areas will be critical to the development of next-generation IPS for Industry 4.0.

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