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Review article

Antennas for indoor positioning: A review of requirements, design considerations, and architectures

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ABSTRACT

Accurate indoor location underpins a wide range of services, from asset tracking in hospitals and campuses to navigation in airports, shopping centers, and large office buildings. Although the Global Positioning System (GPS) is highly effective outdoors, satellite signals are severely attenuated by building materials and are often unavailable in enclosed spaces. Indoor Positioning Systems (IPS) address this limitation by enabling the localization and tracking of people, devices, and assets within buildings. Antenna design is a key determinant of positioning performance in indoor channels, where multipath, electromagnetic interference, and obstruction by metallic structures can bias angle- and time-based measurements. Although IPS technologies are widely studied, a dedicated review of antenna designs for indoor positioning systems remains underexplored.

This review presents an overview of antenna designs for IPS, looking specifically at the unique positioning requirements of indoor systems where obstacles such as metal structure multipath effects will have an impact on antenna performance and position accuracy. We investigate key measurement techniques such as -Angle of Arrival (AoA), Time of Arrival (ToA), and Received Signal Strength (RSS)–and explain their significance for localization in the indoor environment. We also explore various antenna technologies such as Wi-Fi, Bluetooth, Ultra-Wideband (UWB), and millimeter-wave (mmWave). Furthermore, we discuss various antenna types and analyze their respective advantages and limitations for indoor positioning applications. Finally, we summarize emerging directions and open challenges toward robust, infrastructure-efficient indoor positioning.

1. Introduction

Wireless connectivity advances and the growing reliance on location-based services have driven demand for accurate, real-time positioning within buildings. Indoor positioning systems (IPS) address this need by providing location information where satellite navigation fails [1,2]. As a result, IPS has become important across diverse indoor venues—including hospitals, airports, campuses, shopping centres, warehouses, and office buildings—supporting applications such as navigation assistance, asset tracking, occupancy monitoring, and safety services [3]. The ability to manage and optimize interior spaces has thus become vital to meeting the efficiency demands of modern indoor systems [4].

Although Global Navigation Satellite Systems (GNSS) such as GPS have revolutionized outdoor positioning, their performance declines drastically in enclosed environments due to signal blockage, reflection, and attenuation caused by construction materials and indoor infrastructure. This inherent limitation of GNSS necessitates dedicated IPS tailored to the physical and electromagnetic complexity of indoor environments [5].

Indoor environments exhibit uniquely complex radio propagation due to dense multipath from walls, floors, ceilings, furniture, and equipment, often producing significant delay spread and angular dispersion. Dense metallic infrastructure, machinery, and dynamic equipment movement lead to severe multipath propagation, where signals reflect, scatter, and diffract across surfaces. These effects introduce fading, phase distortion, and spatial ambiguity, undermining the accuracy of time- and angle-based localization methods [6]. Non-line-of-sight (NLOS) conditions further degrade performance when obstacles block direct transmission paths, while electric motors,

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welders, and similar equipment generate electromagnetic interference (EMI) that lowers signal-to-noise ratios (SNR) [7]. The resulting degradation in SNR, waveform distortion, and directional ambiguity impairs positioning estimates unless antennas maintain stable behavior under actual indoor propagation condition [8].

Indoor positioning systems rely on a range of wireless technologies, including Bluetooth Low Energy (BLE) [9,10], ultra-wideband (UWB) [11,12] Wi-Fi [13], radio-frequency identification (RFID) [14,15], and millimetre-wave (mmWave) systems [16]. IPS implementations typically build on several fundamental measurement methods: received signal strength (RSS), which infers distance from signal attenuation but is strongly affected by signal variations; time of arrival (ToA), which estimates range from absolute propagation time and therefore requires strict time synchronization; time-difference of arrival (TDoA), which uses relative arrival times at multiple anchors and relaxes synchronization at the transmitter while still demanding tight inter-anchor synchronization; round-trip time (RTT), which relies on bidirectional signalling to estimate distance without global clock alignment; and angle of arrival (AoA), which determines the direction of the incoming wavefront using antenna arrays to enable geometric positioning [17–20]. Depending on the underlying technology and measurement principle, these systems achieve accuracies from the centimetre to the metre scale. Recent work has also investigated deep-learning-based models and reconfigurable intelligent surfaces (RIS) to mitigate multipath-induced errors and enhance localization robustness [21,22].

At the interface between these systems and their environments, the antenna plays a decisive role. As the primary transducer of electromagnetic signals, it not only governs communication efficiency but also determines resilience to propagation impairments such as multipath fading, EMI, and structural obstruction. As a result, antennas deployed in such environments must combine adaptability, robust pattern control, and EMI resistance to sustain accuracy [23,24].

Achieving these characteristics demands coordinated design across the antenna, signal processing, and system architecture. Methods such as spatial diversity, adaptive beamforming, and polarization optimization can mitigate multipath and NLOS effects. Consequently, the antenna ceases to be a passive element and becomes an active contributor to the performance and resilience of indoor IPS [23].

Although improvements in algorithms and sensing architectures continue to enhance IPS performance, the antenna remains a key enabler of practical deployment. Its characteristics—such as gain, bandwidth, polarization, radiation pattern, and directivity—profoundly influence localization accuracy, range, and robustness. Poor antenna design can constrain even advanced IPS frameworks by introducing signal distortion or reducing spatial resolution.

In IPS, antennas serve more than a communication role: they define the reliability of positioning under environmental stress. Directional antennas improve angular resolution and interference suppression [24]; wideband designs support high temporal accuracy [25]; and polarization diversity ensures stable reception across varying orientations [26]. Optimizing these parameters is thus central to maintaining consistent performance in the multipath-dense, electromagnetically noisy settings typical of complex indoor environments.

Therefore, this work is motivated by the critical role that antennas play in the performance of IPS. While various surveys exist for IPS, the design and optimization of the antenna remain a pivotal and active area of research.

As shown in Table 2, previous surveys have primarily addressed IPS technologies, algorithms, and applications, with antennas often treated only as supporting components.

In [27], Geok et al. reviewed radio-wave-based indoor positioning, focusing on underlying principles and performance factors, but without connecting antenna architecture innovations to indoor deployment needs; our work explicitly addresses this gap. A broader perspective was presented in [28], where Qi et al. surveyed meter-level indoor positioning technologies, classifying them into geometry-based, fingerprint-based, incremental-estimation, and quantum-navigation approaches, and comparing them in terms of coverage, robustness, complexity, scalability, and cost. In [29], Shams et al. provided a panoramic survey of indoor positioning systems for IoT applications, covering methods, techniques, enabling technologies, evaluation metrics, and market solutions, but without a targeted examination of antenna design strategies or their adaptation to indoor settings. Likewise, Sesyuk et al. in [30] reviewed 3D indoor localization systems and technologies—including geometric, fingerprinting, sensor-fusion, and hybrid methods—with emphasis on accuracy, strengths, and limitations. However, their review remains technology-agnostic and does not consider antenna design parameters or types, both of which are central to our study.

Costa e Silva et al. in [31] presented a systematic review of radio-wave-based indoor positioning techniques, detailing capture methods (BLE, Wi-Fi, radar, Software Defined Radio) and processing approaches (filtering, fingerprinting). Yet their analysis does not address antenna architectures or their contribution to enhancing localization accuracy under indoor constraints. In [32], Hayward et al. surveyed indoor location technologies, techniques, and applications in industrial cyber-physical systems, comparing inertial, RF, acoustic, and vision-based methods with emphasis on asset and personnel tracking as well as safety. While comprehensive in mapping technologies to industrial use cases, their study does not engage with antenna-level design architectures. Similarly, Li et al. in [33]conducted an extensive review of indoor positioning systems in Industry 4.0, categorizing applications into resource, production, and safety management, and linking technologies such as RFID, BLE, UWB, Wi-Fi, and ZigBee to industrial scenarios. Although their framework highlights the breadth of Industry 4.0 use cases, it does not investigate the specific role of antenna designs in achieving the accuracy, robustness, and scalability required for IPS.

Brás et al. [23] is the only review focused on antennas for indoor positioning. It looks at available designs, organizes them by measurement principle, and outlines the main requirements. While it serves as a baseline, it is over a decade old. Therefore, it does not include newer advancements like MIMO, arrays, leaky-wave antennas, and reconfigurable or metasurface apertures. It also misses their use in modern indoor positioning. A more recent work by Sheikh et al. [34] reviewed antenna designs for indoor, outdoor, and wearable applications. However, its wide focus lacks detail on the antenna architectures, types, deployment challenges, and specific considerations for indoor positioning. In contrast, this review focuses solely on indoor IPS and keeps the antenna at the centre. It connects positioning observables—such as AoA, ToA/TDoA/RTT, and RSS—to the antenna metrics that most affect measurement quality in indoor settings. It also consolidates key antenna design factors and surveys example antenna architectures used in IPS, including planar/patch designs, arrays, MIMO, leaky-wave antennas, reconfigurable methods, and structures inspired by metamaterials and metasurfaces.

Fig. 1 shows an overall picture of this article. This paper is organized as follows. Section 2 summarizes the main indoor positioning technologies. Section 3 reviews the core measurement principles (AoA, ToA, TDoA, RTT, and RSS) and clarifies how each relates to antenna requirements. Section 4 discusses antenna design considerations for indoor environments. Section 5 surveys representative antenna architectures used in indoor positioning. Section 6 highlights emerging trends and open challenges, including 5G/mmWave and passive RIS-assisted positioning. Section 7 concludes the paper. The summary abbreviations is given in Table 1.

2. Indoor positioning technologies

The selection of appropriate antenna technology is fundamental to the performance of IPS within the challenging environments of indoor environments. Various wireless communication technologies are employed for IPS, each with its own characteristics and associated

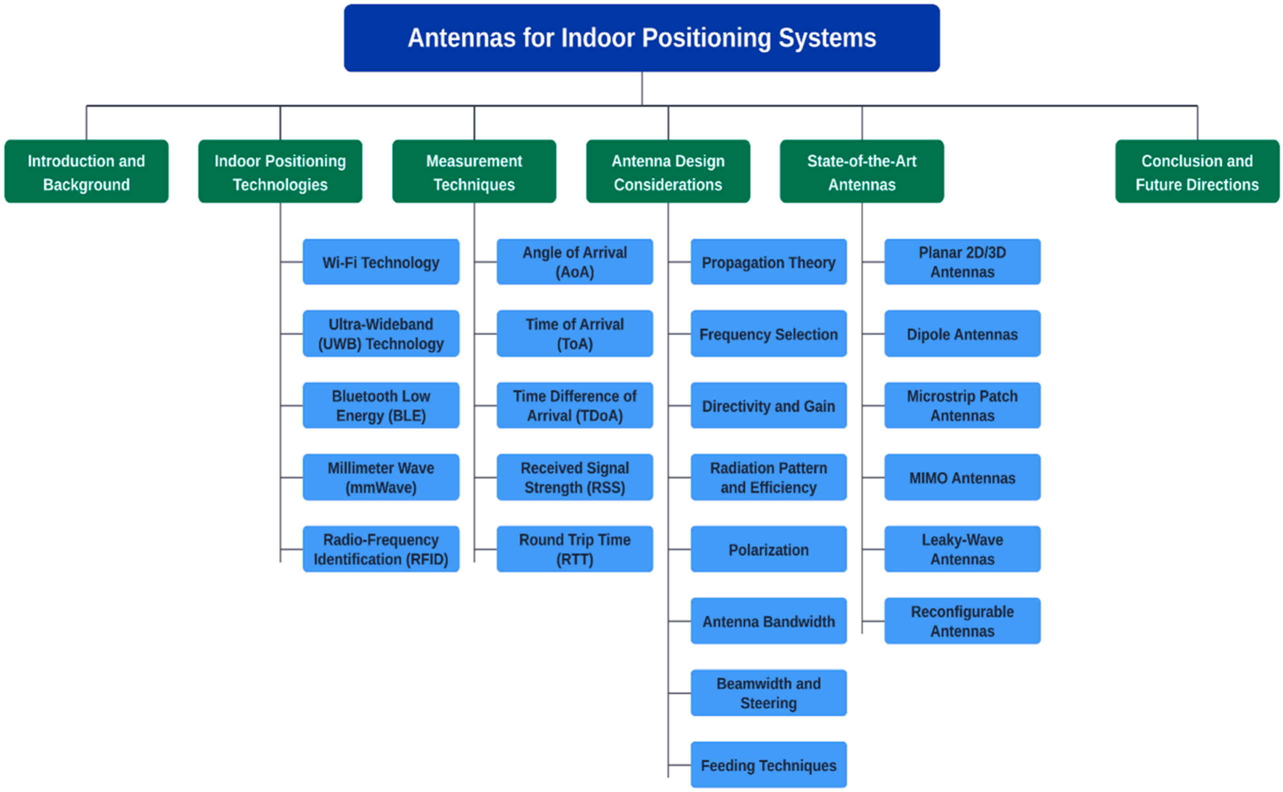

Fig. 1. An overview of the article structure.

considerations.

2.1. Wi-Fi technology

Wi-Fi is one of the most widely adopted wireless networking technologies, operating within the radio frequency spectrum—specifically the 2.4 GHz band for IEEE 802.11b, 802.11g, and 802.11n standards, and the 5 GHz band for IEEE 802.11a [34]. In large indoor settings such as university campuses, airports, and office complexes, Wi-Fi hotspots are strategically deployed to ensure full coverage and provide seamless network access. A wide range of devices rely on this technology, including personal computers, smartphones, tablets, digital cameras, gaming consoles, and portable media players. One of Wi-Fi's key strengths is its relatively low deployment cost for both infrastructure and end-user devices. While early versions supported coverage of only about 100 meters, recent advancements have extended its range to nearly 1 kilometre under optimal conditions [32].

Wi-Fi has become an integral component of indoor localization systems, particularly those based on RSS fingerprinting. It can also be integrated with other RF-based localization approaches, such as RFID, to enhance accuracy and reliability. Compared with Bluetooth, Wi-Fi offers broader coverage and higher scalability, making it a strong candidate for positioning applications in complex indoor environments [35].

Several interesting Wi-Fi antenna approaches have been presented in the literature, employing different antenna configurations and targeting diverse indoor positioning applications. In study [36], a 2.45 GHz smart switched-beam antenna for single-anchor indoor positioning in Wi-Fi/ISM bands is investigated, aiming to avoid the cost and complexity of multi-anchor AoA/ToA systems. The ceiling-mounted antenna uses six circularly polarized microstrip patches on a semi-dodecahedral structure to form overlapping directional beams, with RSS from each beam processed via a MUSIC-based AoA estimator to infer user direction and 2D position. Results in a classroom environment (≈7 × 8 m) show an average localization error of about 1.7 m. The system, however, is evaluated only in a single-room, mostly LOS scenario and exhibits reduced accuracy for users directly beneath the antenna. Another study [37] proposed a Wi-Fi AoA indoor positioning scheme using a passive dual-port frequency-scanned antenna (FSA) connected to a standard MIMO access point. By combining the FSA with channel hopping across the 11 Wi-Fi channels at 2.4 GHz, the system synthesizes 22 frequency-scanned beams and applies an RSSI-only, phase-less MUSIC algorithm to estimate AoA over a 180° field of view, yielding a mean angular error of ≈5.4° at a 3 m link distance with ≈1.1 s RSSI acquisition time—demonstrating that an FSA front-end can enable competitive angle-based indoor positioning. Finally, the authors in [38] introduced a Wi-Fi access-point concept for indoor positioning aimed at low-cost smartphones and IoT devices. The design employs two orthogonal 4-element microstrip patch phased arrays at 5 GHz on FR-4, forming four tilted beams (±12°, ±25°) with about 11.5 dBi gain, each broadcasting a distinct SSID (Wi-Fi network name/identifier) so that a standard Wi-Fi receiver can infer its grid location from the combination of detected SSIDs (Wi-Fi technology, RSS/coverage-based positioning). Nonetheless, the work concentrates on antenna/AP design and beam feasibility, without reporting end-to-end positioning accuracy in practical tests.

While Wi-Fi is attractive due to infrastructure availability, its relatively narrow bandwidth limits time-resolution; UWB addresses this by enabling finer time-based ranging with antenna designs optimized for wideband pulse fidelity.

2.2. Ultra-wideband (UWB) technology

UWB technology has emerged as a promising solution for indoor positioning, offering the potential for high accuracy, often achieving centimetre-level precision. This high accuracy is primarily attributed to its extremely large bandwidth, typically spanning from 3.1 GHz to 10.6 GHz. UWB signals are characterized by their robustness to multipath fading due to the use of very short pulses [39]. Common ranging

Table 1
Summary of important abbreviations.

Abbreviation	Full Term
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
AMC	Artificial Magnetic Conductor
BAVA	Balanced Antipodal Vivaldi Antenna
BLE	Bluetooth Low Energy
BSAA	Beam Switching Antenna Array
BW	Bandwidth
CIR	Channel Impulse Response
CP	Circular Polarization / Circularly Polarized
CPWG	Coplanar Waveguide with Ground
CRLH	Composite Right/Left-Handed
CSI	Channel State Information
CSRR	Complementary Split-Ring Resonator
DGS	Defected Ground Structure
DoA	Direction of Arrival
DRA	Dielectric Resonator Antenna
EBG	Electromagnetic Band Gap
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EMI	Electromagnetic Interference
ESPAR	Electronically Steerable Parasitic Array Radiator
FMCW	Frequency-Modulated Continuous Wave
FoV	Field of View
FR-4	Flame Retardant-4 (PCB substrate)
FSA	Frequency-Scanned Antenna
FTM	Fine Timing Measurement
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HIS	High-Impedance Surface
IoT	Internet of Things
IPS	Indoor Positioning System
IR-UWB	Impulse Radio Ultra-Wideband
ISM	Industrial, Scientific, and Medical (band)
LHCP	Left-Hand Circular Polarization
LOS	Line-of-Sight
LP	Linear Polarization / Linearly Polarized
LWA	Leaky-Wave Antenna
MIMO	Multiple-Input Multiple-Output
MLWA	Microstrip Leaky-Wave Antenna
mmWave	Millimeter-Wave
MUSIC	Multiple Signal Classification
NFC	Near-Field Communication
NLOS	Non-Line-of-Sight
NSA	Null Steering Antenna
PDoA	Phase Difference of Arrival
PDR	Pedestrian Dead Reckoning
RFID	Radio-Frequency Identification
RHCP	Right-Hand Circular Polarization
RIS	Reconfigurable Intelligent Surface
RMSE	Root Mean Square Error
RSS	Received Signal Strength
RTLS	Real-Time Locating System
RTT	Round-Trip Time
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference-plus-Noise Ratio
SIW	Substrate Integrated Waveguide
SNR	Signal-to-Noise Ratio
SPDT	Single-Pole Double-Throw
SP4T	Single-Pole Four-Throw
SP8T	Single-Pole Eight-Throw
SRMP	Single-Radiator Multiple-Port
SSID	Service Set Identifier
TDoA	Time Difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
TSA	Tapered-Slot Antenna
TW-ToA	Two-Way Time of Arrival
UHF	Ultra-High Frequency
UWB	Ultra-Wideband
VLC	Visible Light Communication
VSWR	Voltage Standing Wave Ratio
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

techniques employed with UWB include Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Two-Way Time of Arrival (TW-ToA) [40]. Antenna design for UWB-based IPS requires careful consideration of several factors. A key requirement is a wide bandwidth that covers the operational channel, ideally the entire UWB spectrum. Omnidirectional radiation patterns are often desired to provide uniform coverage across the indoor environment. Additionally, the antenna should exhibit stable characteristics, such as radiation patterns, gain, polarization, and impedance matching, across its entire operating bandwidth [23].

Several UWB antenna solutions for IPS have been proposed, employing diverse designs to provide wide bandwidth, omnidirectional coverage, and, when required, suitable polarization properties. In [41], a compact UWB direction-finding antenna is developed for indoor mobile positioning, targeting space-constrained devices such as smartphones and smart keys. The design uses a single-radiator multiple-port (SRMP) UWB patch on FR-4 with three CPWG-fed ports for AoA-based direction finding, replacing a bulkier multi-element array while maintaining wideband performance. Integrated with a DW3000 UWB transceiver, the antenna achieves a −10 dB bandwidth from 6.3–8.4 GHz and reports average angular errors of about 2.3° over −30° to 30° at 1–2 m. Nonetheless, the evaluation is limited to short ranges, a narrow azimuth sector, and 2D angle estimation, without demonstrating large-scale indoor positioning. In another notable study [42,43], the authors proposed a compact UWB slot antenna for indoor TDoA positioning, using a folded radiating patch with etched slots on a 15 × 20 mm^2 Rogers 4350 substrate to achieve miniaturization and a 3.10–5.74 GHz (≈59.7%) impedance bandwidth. The antenna provides quasi-omnidirectional radiation with realized gain above 2 dBi over most of the band and, when integrated into a multi–base-station UWB TDoA system, yields indoor positioning errors below 2 cm in static tests and around 3–4 cm in dynamic horizontal/vertical movements, i.e., centimetre-level accuracy. However, the design is evaluated only over a partial UWB band and in a single lab environment, so robustness under harsher multipath, NLOS conditions, and across the full band remains unverified.

Another key requirement for UWB reference-unit antennas is circular polarization (CP) across the full band, so that targets with unknown or varying polarization can still be reliably detected [43] .An example of UWB CP antenna is presented in [44] a directional right-hand circular polarization(RHCP)patch for channel 2 that maintains circular polarization over 3.75–4.25 GHz, keeping the left-hand circular polarization (LHCP) component more than 10 dB below RHCP within about ±50° in azimuth, which yields nearly identical received power for co- and cross-oriented tags by reducing polarization mismatch and suppressing opposite-sense reflected paths.

For ease of manufacturing and integration, physically compact and low-profile antenna designs, preferably planar, are generally preferred. While UWB's high accuracy makes it ideal for precision-demanding indoor applications such as autonomous robotics and real-time asset tracking, the cost of specialized UWB hardware, together with the need for a relatively dense infrastructure of synchronized anchors, as illustrated in Fig. 2, can be a limiting factor for some deployments.

2.3. Bluetooth low energy (BLE) technology

BLE has emerged as a prominent technology for indoor positioning, largely due to its cost-effectiveness, minimal power consumption, and broad support across modern mobile devices. Operating in the 2.4 GHz ISM band, BLE is frequently employed with received signal strength

Table 2
Comparison of existing IPS review.

References	Year	Technologies Covered	Primary Focus	Remarks on Antenna Coverage
[23]	2012	RF (WLAN, RFID, UWB)	Antennas for IPS	Foundational review classifying IPS by measurement type (RSS, ToF, AoA); more than 10 years old and now dated.
[27]	2021	IR, Ultrasound, Magnetic, Optical, RF (Wi-Fi, BLE, RFID, UWB, NFC), PDR	General IPS survey	Broad technology overview: antennas are mentioned only as system components.
[28]	2024	Wi-Fi, UWB, 5G, Magnetic Field, CSI, Inertial Navigation	Positioning technologies and methods (geometry-, fingerprint-, and incremental-based)	Focus on positioning methods and algorithms; antenna arrays briefly noted for 5G AoA/beamforming.
[29]	2022	Wi-Fi, BLE, RFID, UWB, VLC, Acoustic, Cellular	IPS for IoT applications	High-level IoT-oriented survey; does not examine antenna design in depth.
[30]	2022	Wi-Fi, BLE, UWB, mmWave, VLC, Sound	3D indoor localization systems	Reviews 3D positioning systems: antenna arrays for AoA are recognised as essential but are not the central topic.
[31]	2025	RF sensors, Wi-Fi, BLE beacons, radar, RFID, UWB	Radio-wave techniques for indoor positioning, human detection, and activity recognition	Concentrates on RF capture and signal processing; antennas are treated mainly as sensing tools, with little design discussion.
[32]	2022	Wi-Fi/WLAN, BLE, WSN, RFID, UWB, Acoustic/Ultrasound, Computer Vision	IPS for industrial IoT (asset tracking, personnel safety, cyber-physical systems)	Industry-focused survey comparing IPS technologies; antennas are only mentioned as parts of the overall systems.
[33]	2024	RFID, BLE, UWB, Wi-Fi, ZigBee	IPS in Industry 4.0	Emphasis on smart manufacturing and logistics applications; antennas are not a main subject.
[34]	2025	BLE, UWB, Wi-Fi, ZigBee, GNSS, wearable antennas	Positioning technologies and antenna designs	Less depth on indoor-specific antenna architectures and measurement-driven requirements
This paper	2025	Wi-Fi, BLE, UWB, RFID, mmWave	Antenna technologies for IPS	Provides an up-to-date, antenna-focused review that addresses design approaches, challenges, and emerging trends.

indication for localization [35].

Antenna designs in BLE-based systems are typically compact and efficient, often integrated directly into the chipset. Because BLE operates under strict power constraints, these antennas are optimized to achieve high transmission and reception efficiency within a small form factor [45].

In [46], a BLE 5.1 AoA self-localization system using an 8-element circular antenna array at 2.4 GHz on the mobile node is implemented for indoor Industry 4.0 applications. AoA is estimated from phase differences of BLE direction-finding packets and combined via least-squares triangulation from several fixed omni BLE beacons, yielding ≈10.7° AoA RMSE and ≈3.6 m mean position error (minimum 1.1 m) over a 12 × 12 m area, i.e., meter-level indoor/outdoor positioning suitable for self-navigating industrial assets. However, the system is evaluated mainly in static tests with a single prototype, and the accuracy remains at meter scale in realistic multipath environment. The authors of [9] investigated BLE 5.1 AoA performance using a compact 3 × 3 uniform rectangular arrays of circularly polarized octagonal microstrip patches at 2.4 GHz, motivated by the need for miniaturized BLE locators that still deliver accurate angle-based indoor positioning. By employing embedded radiation patterns that capture mutual coupling and platform effects together with MUSIC/Bartlett processing, they show that $\lambda/2.5$ element spacing, and ERP-based modelling significantly reduce azimuth/elevation error and enable reliable single-snapshot AoA estimates for SNR > 20 dB, indicating strong potential for accurate BLE AoA indoor localization. In another notable study [47], the authors proposed a BLE-based indoor localization front-end using a custom four-port frequency-steered leaky-wave antenna (LWA) array that synthesizes twelve narrow, overlapping beams across a 120° azimuth sector by exploiting the three BLE advertising channels. The system uses BLE RSSI measurements at a single-antenna receiver and applies amplitude-monopulse–style processing to estimate the direction-of-departure (DoD), thereby avoiding phased arrays or active RF beamforming. Experimental results demonstrate angular RMSE of approximately 2.6° in anechoic conditions and 3.7° in realistic environments, highlighting the suitability of the proposed antenna for high-resolution BLE-based angular localization. However, the approach remains limited to 2D angular estimation with a single beacon and 1 dB RSSI quantization, without extending to full 3D localization.

BLE provides an attractive trade-off between cost, energy efficiency, and accuracy, particularly with the introduction of Angle-of-Arrival (AoA) capabilities that improve positioning performance. However, its comparatively short communication range, when measured against Wi-Fi or UWB, often requires a denser deployment of beacons or anchor nodes in large-scale indoor environments to guarantee continuous coverage. Despite this limitation, the low complexity and power requirements of BLE make it highly suitable for applications such as workforce monitoring, proximity-based safety alerts, and localized asset tracking in indoor settings.

2.4. Millimeter-wave (mmWave) technology

Millimetre-wave (mmWave) technology, operating in the 30–300 GHz frequency range, offers distinctive characteristics that make it highly relevant to indoor positioning environments [48]. The vast bandwidth available at these frequencies enables not only ultra-high data rates but also fine-grained positioning accuracy. Millimetre-wave operation leverages very short wavelengths, which enable the integration of dense, compact antenna arrays capable of sophisticated beamforming [49]. By steering energy into narrow, highly directive beams, such arrays can partially compensate for the severe propagation losses encountered at mmWave frequencies .Consequently, mmWave-based IPS typically employ large or even massive arrays to achieve sufficient array gain and angular selectivity. These systems adopt analog, hybrid, or fully digital beamforming architectures, with each option presenting a different balance between hardware complexity, implementation cost,

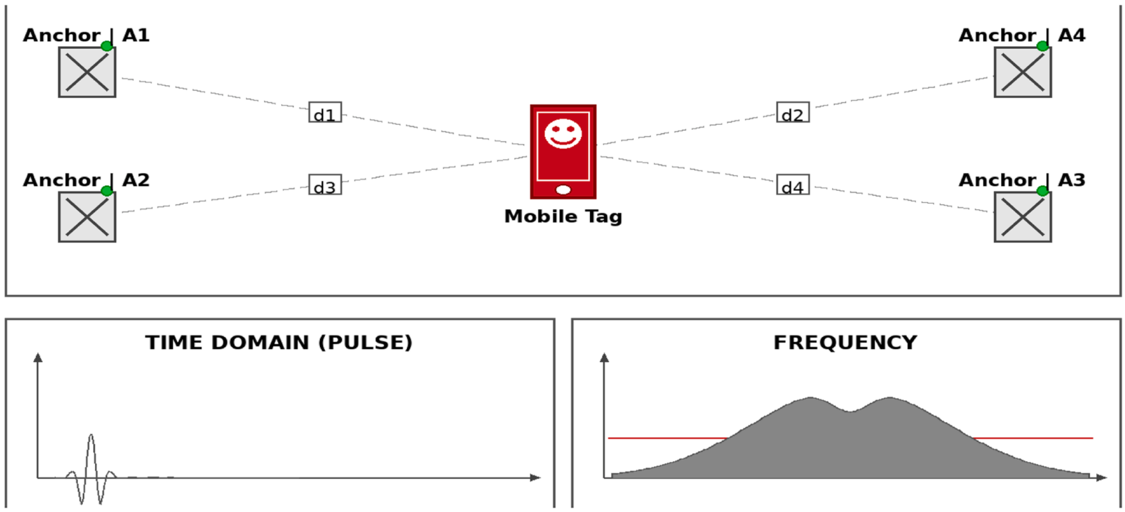

Fig. 2. Basic elements of UWB positioning system.

and attainable localization accuracy [48,50]. For example, in [16], a 60 GHz mmWave indoor sensing and localization system ("mmReality") is demonstrated using 16-element phased-array antennas at both transmitter and mobile receiver, leveraging joint AoA/ToF processing for high-accuracy positioning. The system steers analog beams to capture LOS and first-order NLOS multipath, applies 2D-MUSIC to estimate AoAs/AoDs, and uses multi-carrier OFDM ranging to recover path lengths, enabling room-layout reconstruction and receiver localization; experiments in corridor and office scenarios report $\approx$0.42 m average layout error and $\approx$1.0 m positioning error (90% $<$ 1.3 m).

Recent trends in mmWave indoor localization use leaky-wave antennas as compact replacements for bulky phased arrays in high-resolution angle estimation. For instance, in [51] a planar Bull's-Eye leaky-wave antenna (LWA) operating from 14–32 GHz is investigated. The printed concentric-ring LWA exploits backward and forward frequency scanning to form vertically polarised conical beams over a wide elevation field of view (FoV). A frequency-domain MUSIC algorithm then processes the scanning response to recover AoA. Simulations report DoA RMSE down to $\approx 1.3^\circ$ over 0–90° elevation with 1 GHz steps at 20 dB SNR. With denser sampling, the error improves to $\approx 0.03^\circ$. These results show that a carefully engineered mmWave LWA front-end can deliver very fine angular resolution for AoA-based indoor positioning. However, the work is purely simulation-based, with no end-to-end indoor localization experiments.

Overall, in indoor settings, mmWave technology shows strong potential for high-precision IPS, particularly in applications requiring high bandwidth and low interference, such as areas with autonomous mobile robots or for high-throughput data exchange between machines. Nevertheless, its deployment faces notable challenges: mmWave signals are highly susceptible to blockage from obstacles such as machinery and human presence, and their directional nature requires sophisticated beam management to maintain continuous connectivity and accurate positioning of moving assets.

2.5. Radio-frequency identification (RFID)

RFID offers a low-power, cost-effective solution for a range of indoor positioning applications, particularly in asset tracking and proximity-based localization within indoor environments. An RFID system generally comprises readers and tags. Passive tags, which are most common in industrial settings, do not require an internal power source but instead harvest energy from the interrogation signal of the reader [52].

RFID systems use a reader connected to an antenna to emit electromagnetic signals that are received by RFID tags. For localization and tracking, the most relevant band is ultra-high frequency (UHF) RFID, operating between 300 MHz and 3 GHz, where reported read ranges typically exceed 1 m. This extended range makes UHF RFID the primary choice for indoor location and asset-tracking applications [32].

The performance of RFID systems, including both read range and reliability, is strongly influenced by the antenna design of both reader and tag, as well as by environmental conditions—particularly the presence of metallic surfaces and other obstructions that can disrupt signal propagation [53] .For indoor positioning, the design of RFID reader antennas often prioritizes circular polarization, as this reduces sensitivity to tag orientation—a crucial feature in industrial contexts where assets are frequently moved or stored in unpredictable orientations. Reader antennas are also designed with relatively high gain to extend read range and with low side-lobe levels to reduce interference from unintended tags or multipath reflections [54].

The use of appropriately designed antennas in RFID positioning systems has been documented in several studies. The authors in [14] proposed an RSSI-based AoA localization method using two orthogonal pairs of directional RFID antennas. The angle of arrival is inferred from the axial RSS sensitivity of each antenna pair, and the tag position is then obtained by triangulating the angles from the two pairs. In measurements, the system achieved a localization accuracy of 1.15 m, with 90% of position estimates within this error over a 12 m^2 area. In [55], a custom 2.45 GHz active RFID reader based on a compact 2-D patch antenna array is developed. It uses monopulse beam steering in azimuth and elevation to enable AoA estimation and RSS-based 3D indoor localization and fall detection, scanning about $\pm 45^\circ$ in both planes and achieving decimetre-level accuracy (average errors $\lesssim$20 cm) in realistic rooms. However, the system relies on active tags, room-specific calibration, and is validated only in limited indoor areas within the 2.45 GHz ISM band. Finally, the authors in [56] designed a wearable metasurface-enabled quasi-Yagi UHF RFID reader antenna on a textile forearm band to support pointing-based AoA indoor positioning, using a co-optimized periodic surface to restore end-fire radiation and achieve about 5.9 dBi directivity and 5.5 dBi realized gain along the arm. Wireless tests at 915 MHz show a read range of about 3.8 m at 32 dBm reader power, enabling meter-scale, directionally constrained RFID indoor localization for smart-clothing and e-health applications.

RFID is well-suited to tasks such as inventory management, checkpoint-based tracking of goods, and access control in indoor facilities. However, its ability to provide precise spatial coordinates is generally inferior to higher-resolution technologies such as UWB or mmWave. Table 3 summarizes the key characteristics and trade-offs of the reviewed indoor positioning technologies.

Table 3
Comparison of indoor positioning technologies.

Technology	Accuracy Level	Hardware Costs	Advantages	Disadvantages
Wi-Fi [34]	1-10 m	Medium	Widely used, Easy to deploy	Easy to interfere with Multipath problem
Bluetooth [45]	1-5 m	Low	Wide application Low-power consumption	Path loss Easy to interfere with
mmWave [48]	0.1–1 m	High	High data rates, wide bandwidth, high positioning accuracy, low latency	Short range, easily blocked by obstacles, high cost
RFID [52]	1-5 m	Low	High positioning accuracy Easy to deploy	Need Environmental Transformation, Multipath problem
UWB [39]	Centimetre-level	High	High positioning accuracy Anti-interference, High multipath resolution	High cost, complex deploy

3. Indoor positioning measurements

Accurate indoor positioning relies on various measurement techniques that extract spatial information from received signals. These techniques differ in their working principles, accuracy, cost, and suitability for various environments and applications. We focus on the five measurement families most relevant to antenna design: AoA, ToA, RSS, RTT, and TDoA.

3.1. Angle of arrival (AoA)

Angulation is a variation of the triangulation technique, commonly referred to as the Angle of Arrival (AoA) or Direction of Arrival (DoA). It estimates the location of the target by computing angles relative to multiple reference points, as shown in Fig. 3. These angles can be determined with respect to the unit itself, an electronic compass, or a second received signal [57]. AoA requires at least two APs and sets up array antennas or directional antennas to obtain the angle information of the target and AP. AoA has a simpler structure than the above two algorithms but is seriously affected by non-line-of-sight. The positioning accuracy depends on the accuracy of the antenna array and requires regular inspection and maintenance. One key advantage of this technique is that if the orientation of the mobile unit is known, only two measurements from no collinear reference nodes are required for 2D localization, while three are needed for 3D localization. Additionally, unlike Time of Arrival (ToA), AoA-based localization does not require time synchronization between units [23]

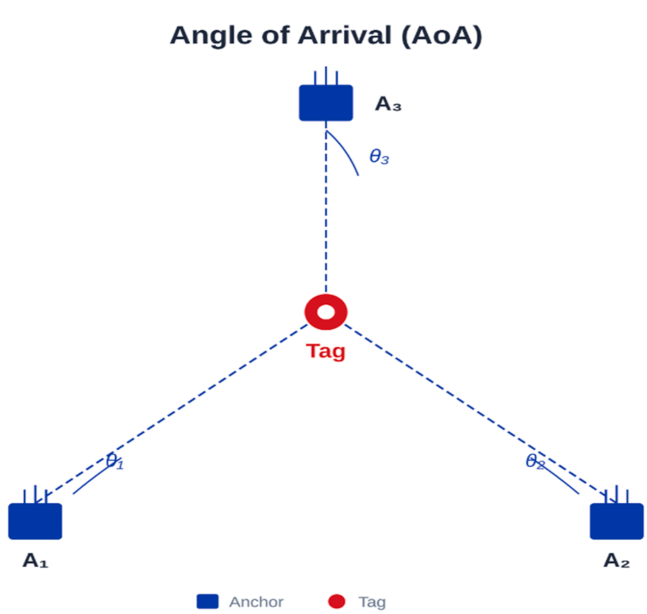

Fig. 3. AoA positioning technique.

AoA localization is inherently antenna-dependent, since the estimated angle is determined by how the antenna receives and resolves incident wavefronts. Multipath propagation, shadowing, and the intrinsic directivity of the antenna all influence the angular estimate, so the antenna becomes a primary determinant of system accuracy [17]. This imposes strict constraints on the antenna design. Narrowband AoA systems favour narrow beams and circular polarization, whereas UWB counterparts require large bandwidth, stable phase response, and low mutual coupling between elements. To maintain compactness and manufacturability, most realizations employ planar structures [23].

AoA estimation is commonly implemented using three main antenna classes: steerable parasitic array radiator (ESPAR) antennas with tunable parasitic elements [58], linear or planar phased arrays with controlled phase and amplitude [10], and sectorised arrays composed of multiple fixed directive antennas that together provide azimuthal or hemispherical coverage [59].

A wide range of studies has investigated different antennas for AoA-based indoor positioning [17,60]. For example, in [61] the authors examined the AoA performance of a compact dual-antenna UWB reader based on the DW3220, using two $\lambda/2$-spaced chip antennas at 6.5 GHz and phase-difference-of-arrival processing. The node estimates both distance and bearing, but its main contribution lies in its angular performance, achieving sub-degree mean AoA errors ($\approx 0.6^\circ$ within $\pm 45^\circ$ and $\approx 2.4^\circ$ RMSE over 0.5–5.5 m) together with centimetre-level ranging. However, the evaluation is restricted to 2D LOS and a limited angular sector, and performance degrades outside the main $\pm 45^\circ$–60° field of view. In another study [62], the authors proposed a dual-band 2.45/5.2 GHz circularly polarised switched-beam Wi-Fi anchor to enhance azimuthal AoA estimation using only RSS. By matching the dual-band beam RSSI patterns to analytical cardioid models, the system achieves mean azimuth errors of about 2.6° in quasi-LOS and $\approx 4.9^\circ$ in a 50 m^2 area with strong synthetic wall reflections, with 90% of errors below 10.5°, although the evaluation remains limited to single-anchor azimuth tracking in controlled environments.

However, the main drawbacks of this technique stem from its large and complex hardware requirements. Accurate localization depends on precise angle measurements, which tend to become less reliable as the unit moves farther from the measuring device. Furthermore, AoA-based systems are highly susceptible to errors caused by multipath effects and the directivity of the receiving antennas.

3.2. Time of arrival (ToA)

In the ToA technique, the arrival time of a signal from the transmitter to at least three known nodes are measured. By considering each node as the centre of a circle and the estimated distance as the radius, three circles are defined. The object's location is then determined at the intersection of these circles as shown in Fig. 4. ToA is essentially the same technique used in GPS systems. Its primary advantages include high precision and straightforward mathematical formulation [63,64] .

Several studies have investigated different antennas for ToA-based indoor positioning [17,65]. For example, in [66] the authors proposed a UWB 3D localization setup using a fingertip-sized body-mounted tag and three compact Vivaldi base-station antennas. ToA was extracted

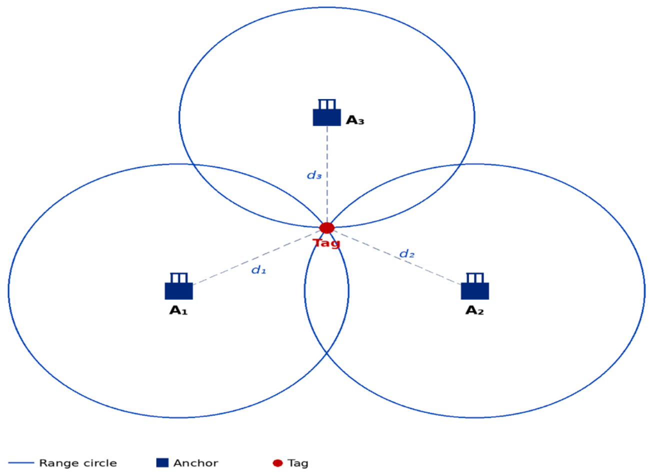

Fig. 4. ToA positioning technique.

from the UWB channel impulse response and refined by modelling the antenna phase centres and applying simulation-based offsets, reducing 3D localization error from about 1–4 cm to roughly 0.4–0.8 cm in indoor LOS tests. In [67], the authors developed a Wi-Fi ToA/TDoA indoor positioning method that derives high-resolution ToA from the IEEE 802.11g long training symbol using baseband cross-correlation with sub-sample phase refinement, then forms TDoA across synchronized receivers for trilateration. In LOS corridor tests with directional panel antennas and 40 MHz sampling, the system achieves mean 1D errors of about 0.42–0.67 m and 2D errors around 1–1.5 m for half of the estimates, demonstrating sub-meter ToA-based performance using standard Wi-Fi hardware, though validation is mostly limited to cabled synchronization and low-multipath scenarios. In another study [68], a hybrid UHF/UWB passive tag antenna is designed to enable centimetre-level indoor positioning using UWB ToA ranging. The crossed exponentially tapered slot UWB radiator is tailored for a stable phase centre and low pulse distortion, allowing ToA-based trilateration with three anchors to achieve ≈2 cm mean 2D error at 1 m and distance errors below ∼5% up to 6.5 m in indoor LOS. These results highlight how wide, low-dispersion bandwidth and careful antenna design can significantly improve ToA accuracy.

However, the main drawback of ToA is its reliance on time synchronization between all nodes and the target object. Even a slight mismatch of a few milliseconds can lead to significant inaccuracies in distance estimation.

3.3. Received signal strength (RSS)

RSS, as shown in Fig. 5, refers to the signal power measured at the receiver and is frequently employed to estimate the distance between devices using signal attenuation models, often approximated by a log-normal distribution [64] . Distance estimation is typically carried out by converting signal strength into range values and localizing the mobile unit through trilateration, which involves calculating the intersection of three circles cantered at reference nodes. This approach is attractive because it is simple to implement and incurs minimal cost, as most wireless receivers are already equipped with RSS measurement capabilities [69].

In practice, however, RSS-based distance estimation is highly sensitive to environmental conditions. In indoor settings, where maintaining a clear LOS is difficult, measurements are strongly influenced by multipath fading, shadowing, and antenna-specific characteristics [70]. These effects complicate the development of mathematical channel models that accurately capture real propagation conditions, often resulting in significant localization errors [71].

To address these limitations, several antenna-based approaches have been proposed to improve RSS reliability [72–74] .For instance in [72], a dual-band circularly polarised switched-beam Wi-Fi anchor operating at 2.45/5.2 GHz, using six directive beams and space–frequency diversity to enable RSS-based 2D indoor positioning with a single ceiling-mounted access point, is proposed. Position is estimated by matching measured RSS vectors to precomputed power maps and fusing multi-frequency data, achieving mean errors of ≈31–37 cm and 90th-percentile errors around 52 cm in a 25 m^2 area, although the results are limited to static users and a small, controlled indoor environment. A related approach in [75], a 2.4 GHz BLE indoor positioning system is

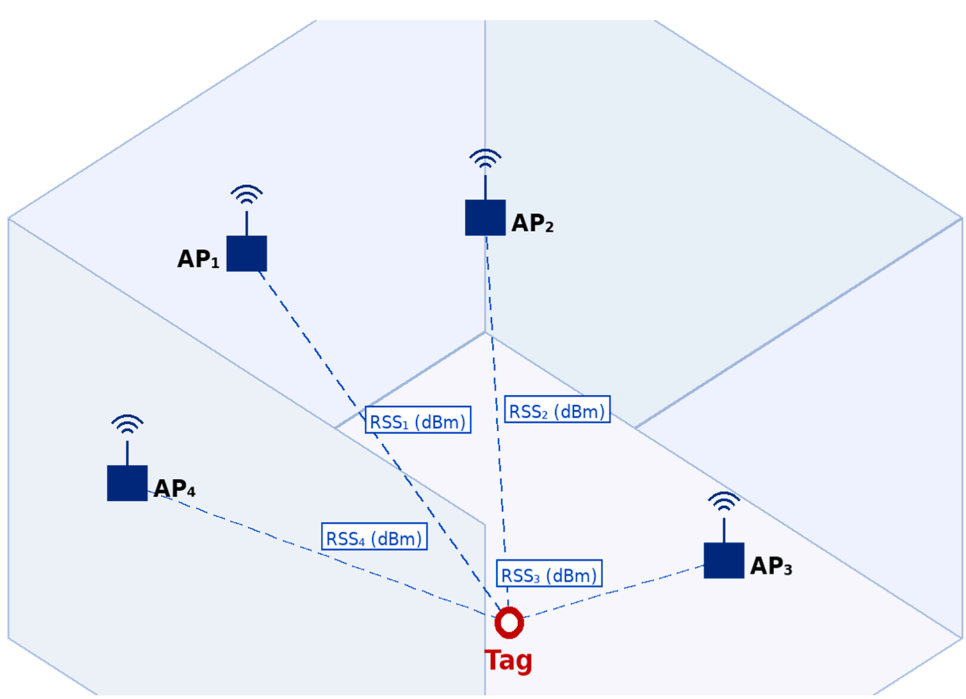

Fig. 5. RSS positioning technique.

implemented using a microstrip leaky-wave "GHz prism" antenna to shape the RSS of the three BLE advertising channels into 12 directive beams for separate-channel fingerprinting; with a single ceiling-mounted anchor in a 3 m × 12 m corridor, the RSS fingerprinting error is reduced from 160 cm to 94 cm, showing that carefully engineered radiation patterns can significantly improve RSS-based indoor localization, though accuracy remains at the metre scale in a simple testbed.

3.4. Round trip time (RTT)

RTT, or Fine Timing Measurement (FTM), is an indoor positioning method standardised under IEEE 802.11mc [28] . It determines distance by timing signal travel between a mobile device and fixed access points, averaging multiple measurements to improve accuracy. Position is then resolved through trilateration using distances from at least three base stations with known coordinates as shown in Fig. 6 [76]. Unlike signal-strength methods, RTT depends solely on temporal measurement, reducing sensitivity to antenna orientation and beam width. Sub-meter accuracy is achievable under line-of-sight conditions, though multipath and obstructions introduce ranging errors. Because RTT measures flight time rather than signal amplitude, it overcomes limitations tied to antenna configuration and directionality that constrain other wireless positioning approaches [23].

In practice, the measured RTT corresponds to the signal's round-trip propagation time across the link, combined with the processing delay at the responder. With appropriate synchronization support, this method can even be extended to passive RFID systems, where the reader units not only interrogate but also energize the tags, enabling time-based ranging for localization [23].

In RTT-based indoor positioning, the antenna determines how far and how cleanly the two-way time-of-flight signal can travel, since its gain, pattern, and polarization govern link budget, and the stability of the measured round-trip time [18] . Several recent works illustrate how antenna design choices shape RTT system performance. For example, in [77] the authors implemented a Wi-Fi RTT-based active monopulse radar that employs a single 802.11mc access point with two tilted directive panel antennas to localize RTT-capable devices by combining round-trip time ranging with RSSI-based amplitude-monopulse AoA estimation. The design aims to avoid multi-AP deployments and complex CSI processing while still achieving sub-meter indoor positioning. Measurements in a corridor testbed reported mean 2D localization errors below 1 m within a ±30° field of view and up to 14 m range, using only commercial Wi-Fi hardware and standard FTM frames. However, performance degraded at very short ranges and outside the calibrated angular sector, restricting coverage to a relatively narrow FoV.

In another study [44], the authors upgraded a UWB two-way RTT system by replacing low-gain omnidirectional monopoles with compact, higher-gain UWB patch antennas providing approximately 180° coverage and circular polarization, extending the LOS RTT reading range from about 82 m to 175 m and yielding smoother indoor links with reduced dependence on tag orientation over a 50 m corridor. Finally, in [18] a planar half-width microstrip leaky-wave Wi-Fi antenna is integrated with a 2 × 2 MIMO RTT-capable access point to enable single-AP indoor positioning by combining AoA from RSSI with range from RTT at 2.4 GHz. Anechoic-chamber tests over 0.5–3 m and ±90°FoV report mean angular errors below approximately 1.8°, range errors below approximately 0.8 m, and 2D position errors under approximately 30 cm for 90% of estimates. However, the evaluation is confined to short ranges and a low-multipath environment.

3.5. Time difference of arrival (TDoA)

TDoA, as shown in Fig. 7, is a positioning technique that localizes a transmitting object by measuring the differential arrival times of its signal at multiple receiver locations. The fundamental principle relies on hyperbolic trilateration: each time difference defines a hyperbola of possible positions, and the intersection of multiple hyperbolas yields the transmitter's precise coordinates [76].

The system architecture comprises a minimum of three spatially distributed receiver antennas and a central processing unit for time difference computation. Antenna configuration constitutes a critical design parameter—strategic placement at elevated positions maximizes line-of-sight coverage, while receiver antenna orientation directly influences angle-dependent waveform distortion and overall localization accuracy [64] .

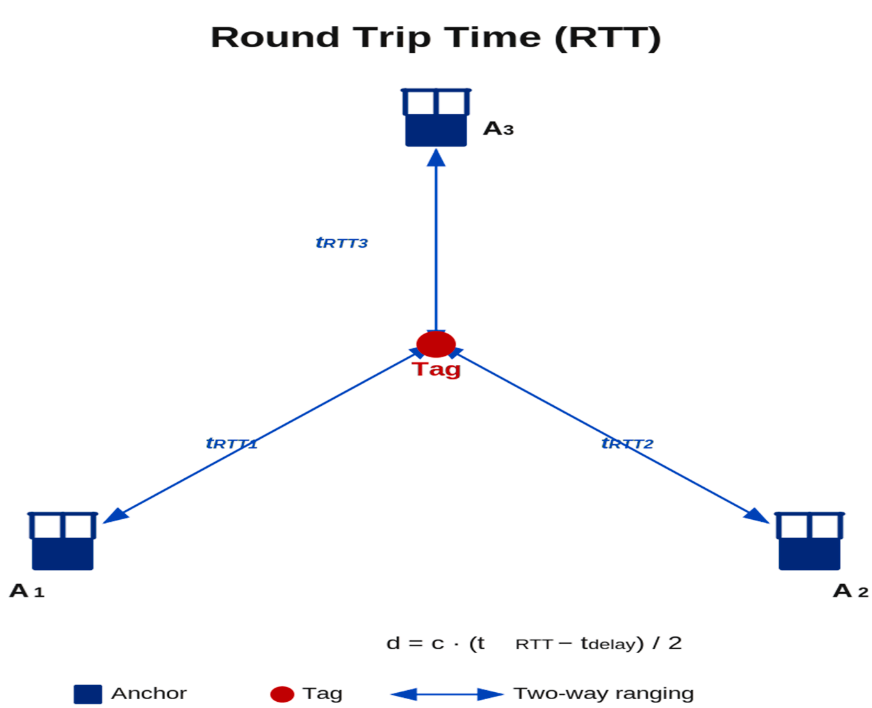

Fig. 6. RTT positioning technique.

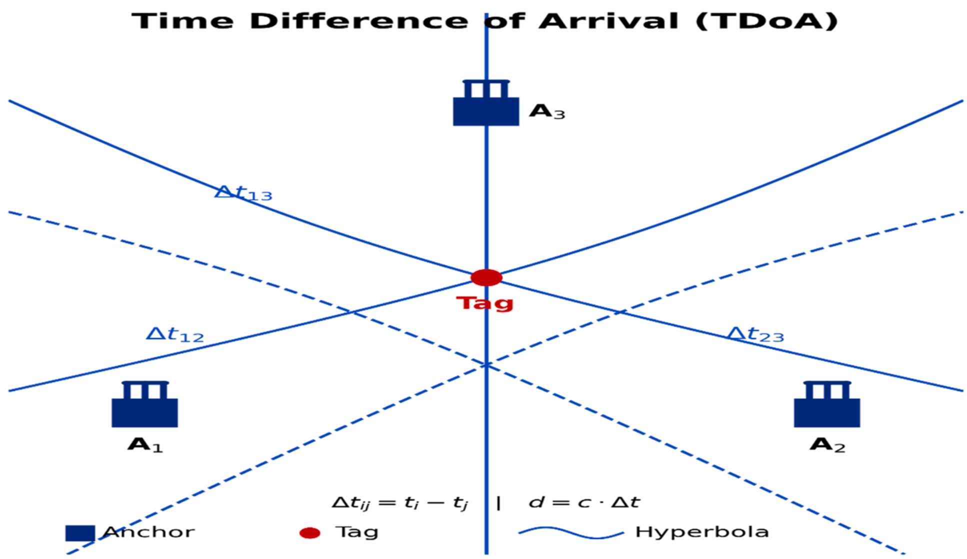

Fig. 7. TDoA positioning technique.

TDoA is predominantly employed in UWB indoor positioning systems due to its capacity for centimetre-level precision, making it suitable for applications requiring high accuracy such as tracking miniature mechanical components in indoor settings and asset monitoring in complex environments. The technique is favoured because it eliminates the need for transmitter-receiver synchronization, relying solely on relative time measurements between receivers [19,40].

Several studies have investigated different antenna designs for TDoA-based indoor positioning, focusing on optimizing antenna bandwidth to enhance signal reception and mitigate multipath effects. In [78], a body-centric UWB indoor localization system using compact wearable monopole antennas and three fixed anchors is evaluated with TDoA-based multilateration to track a moving person. After LOS/ NLOS classification, the TDoA processing achieved 2D localization errors of about 0.5–3 cm over 0.4–5 m in an office environment, demonstrating that wideband antennas with good signal fidelity can enable centimetre-level TDoA performance. However, the study is restricted to a small, single-user, UWB-only testbed with environment-specific training, so its scalability to larger, multi-user indoor deployments was not demonstrated. A related body-centric study [79] extended wearable UWB localization to three dimensions, using tapered-slot UWB antennas (2.2–11 GHz) mounted on the human body and four fixed UWB anchors. The wide bandwidth and body-optimised radiation patterns enabled very sharp discrimination of arrival-time differences between anchors, allowing TDoA-based trilateration to achieve approximately 1–3 cm 3-D errors in a $1.5 \times 1.5 \times 0.8\ m^3$ indoor volume, although performance was only validated in a LOS scenario.

Beam-steering techniques offer an alternative approach to improving TDoA accuracy. In [43], a TDoA-based indoor Wi-Fi localization system at 2.45 GHz is introduced, using a beam-steering broadband circularly polarized receive antenna to enhance time-difference measurements. TDoA was obtained by cross correlating the WLAN signals received at three anchors, while electronic beam switching was applied so that the correlation peak was dominated by the LOS path rather than multipath. In 2D indoor tests with 20 MHz bandwidth, mean positioning errors of about 0.7–0.82 m is achieved, representing at least a 51% improvement over a system using an omnidirectional antenna, although performance in dense NLOS or dynamic environments is not assessed.

Table 4 compares measurement techniques for indoor positioning based on their principles, advantages, and limitations.

Table 5 shows that positioning performance is closely linked to the selected observable and the corresponding antenna characteristics. AoA relies on antenna arrays with stable phase behavior, enabling direction estimation but remaining sensitive to multipath and calibration errors [80]. Time-based approaches, including ToA, TDoA, and RTT, provide higher ranging accuracy through large bandwidth and precise timing, though they require careful synchronization or additional signalling and are affected by delay distortion and NLOS conditions [81]. In contrast, RSS-based methods are easier to deploy but offer lower accuracy, with performance strongly influenced by device orientation, fading, and

Table 4
Comparison of measurement techniques for IPS.

Technique	Working Principle	Advantages	Disadvantages	Hardwar cost
AoA [43]	Estimates location by measuring the angle of signal arrival at a receiver from multiple reference points.	Potential for high accuracy can exploit multipath, with no fingerprinting or mobile device synchronization needed.	Susceptible to correlated signals, higher computational complexity, accuracy decreases with distance and requires specialized antennas.	Medium–High
ToA [34]	Measures the travel time of a signal to calculate distance.	High localization accuracy, no fingerprinting database needed.	Requires precise time synchronization between transmitter and receiver, influenced by multipath and noise, needs specialized hardware.	Medium–High
RSS [44]	Estimates distance based on signal power, using path loss models or fingerprinting.	Low cost, easy to implement, no synchronization needed, can use existing Wi-Fi.	Lower accuracy suffers from multipath and noise, environmental dependency for fingerprinting.	Low
RTT [38]	Measures the time for a signal to travel to a node and back.	No time synchronization is needed between transmitter and receiver, with relatively low complexity.	Affected by multipath and noise, processing delays can occur, not universally	Low–Medium
TDoA [45]	Estimates location by measuring the difference in signal arrival times at multiple synchronized receivers.	High accuracy, no synchronization needed for the mobile device, scalable in downlink systems.	Requires precise synchronization between receivers, complex in a narrow bandwidth, affected by multipath.	Medium–High

Table 5
Performance and deployment characteristics of IPS techniques.

Observable	Antenna Design Requirements	Calibration Requirements	Accuracy (LOS)	Deployment Constraints	Main Failures
AoA [61, 83]	Array (≥2 elements), λ/2 spacing, phase-coherent; large aperture, inter-element phase stability; moderate bandwidth; directional radiation pattern	Steering vector estimation; inter-element phase alignment; mutual coupling calibration	∼1°–10° angular error	≥2 anchors; multiple RF chains; calibration required	Multipath, phase synchronization errors, mutual coupling
ToA [84]	Wide bandwidth (≥500 MHz UWB); flat group delay; near omnidirectional radiation pattern; stable polarization across operating band	Antenna delay calibration; group-delay compensation	10–30 cm	Precise timing required; high-bandwidth radios	NLOS bias, pulse distortion
TDoA [85]	Same as ToA; single-antenna per anchor; near-omnidirectional radiation pattern	Antenna delay calibration; sub-nanosecond synchronization between anchors	∼10–50 cm	Sub-ns anchor synchronization (1 ns ≈ 30 cm); network complexity	Clock synchronization error, NLOS bias
RTT [76]	Wide bandwidth (UWB); stable group delay; consistent polarization	Antenna delay calibration; no inter-anchor synchronization required	∼10–30 cm	No synchronization required; requires message exchange; limited capacity	Clock drift, NLOS bias
RSS [82]	Stable and uniform radiation pattern; polarization consistency; orientation sensitivity; polarization diversity recommended	Device-specific calibration; environment-dependent calibration	1–5 m	Offline site survey; device-specific calibration	Orientation effects, fading, environmental changes

environmental variations [82].

Across AoA, time-based ranging (ToA/TDoA/RTT), and RSS, the antenna is not a passive component: its bandwidth and dispersion shape timing fidelity, its phase centre and mutual coupling shape angular estimates, and its radiation pattern and polarization shape link stability under multipath and device orientation changes. These dependencies motivate the antenna design considerations consolidated in the next section.

4. Antenna design considerations for indoor positioning systems

The performance of indoor positioning systems is strongly influenced by the fundamental parameters of the antennas employed. Selecting appropriate antenna characteristics is essential for achieving accurate and reliable localization within indoor environments, where multipath propagation, signal attenuation, and interference present significant challenges. In this section, an overview of key antenna parameters will be presented, focusing on their impact on indoor positioning accuracy and system design.

4.1. Antenna requirements across positioning techniques

The positioning techniques discussed in the previous section rely on different signal observables, and these differences translate directly into distinct antenna design requirements. Each method extracts information from the received signal in its own way, whether through angle, propagation time, or signal strength, and the antenna therefore has a direct influence on how accurately this information can be captured.

In angle-of-arrival (AoA) systems, direction is inferred from phase or amplitude differences across multiple antenna elements. This makes array geometry, element spacing, and phase consistency critical, as even small mismatches or coupling effects can introduce angular bias, especially in compact arrays [86]. For time-based techniques such as time-of-arrival (ToA), time-difference-of-arrival (TDoA), and round-trip time (RTT), the focus shifts to delay estimation. Here, the antenna becomes part of the propagation path, and its frequency response directly affects timing accuracy [69,87]. While wide bandwidth is necessary, stable group-delay behaviour and controlled antenna delay are equally important, since variations translate into systematic ranging errors, particularly in ultra-wideband systems [88].

In received-signal-strength (RSS)-based positioning, the emphasis is different again. Since localization depends on signal power, the antenna must provide stable and predictable radiation characteristics [20]. Variations in pattern, polarization mismatch, and device orientation can significantly distort the relationship between signal strength and distance, which is why near omnidirectional and robust designs are typically preferred [23].

Taken together, these differences show that antenna design is closely tied to the chosen positioning observable, as summarized in Table 5. Further discussion of key antenna parameters follows in the next subsections.

4.2. Propagation theory of EM waves in indoor environments

The propagation of electromagnetic (EM) waves in indoor environments is significantly different from that in free space or outdoor settings. Indoor propagation is characterized by several phenomena that need to be carefully considered in antenna design for positioning applications, as shown in Fig. 8. Path loss, the attenuation of signal power as it travels through space, is exacerbated by the presence of walls and other obstacles within indoor setting [89]. Reflection occurs when EM waves encounter surfaces with different electrical properties, leading to multiple signal paths arriving at the receiver [90]. Refraction is the bending of EM waves as they pass from one medium to another with a different refractive index. Scattering happens when waves encounter objects with dimensions comparable to or smaller than the wavelength, causing the waves to be dispersed in multiple directions [91]. Diffraction allows EM waves to bend around obstacles, enabling signal reception even when there is no direct LOS [7].

Multipath fading is another significant challenge in indoor environments, resulting from the superposition of multiple delayed and attenuated copies of the transmitted signal arriving at the receiver. This can cause fluctuations in signal strength and phase, leading to errors in positioning measurements [43]. Addressing these propagation characteristics is crucial for designing antennas that can effectively transmit and receive signals in the complex and dynamic electromagnetic environment of the indoor setting.

4.3. Frequency selection

The selection of the operating frequency band is a critical design decision for IPS, as it directly influences range, data rate, susceptibility to interference, and overall system performance. Several frequency bands are commonly used or under investigation for indoor localization applications.

RFID systems use a reader connected to an antenna to emit electromagnetic signals that are received by RFID tags. For localization and tracking, the most relevant band is ultra-high frequency (UHF) RFID, operating between 300 MHz and 3 GHz, where reported read ranges typically exceed 1 m. This extended range makes UHF RFID the primary choice for indoor location and asset-tracking applications [32].

The 2.4 GHz band, widely employed for Wi-Fi and BLE, offers

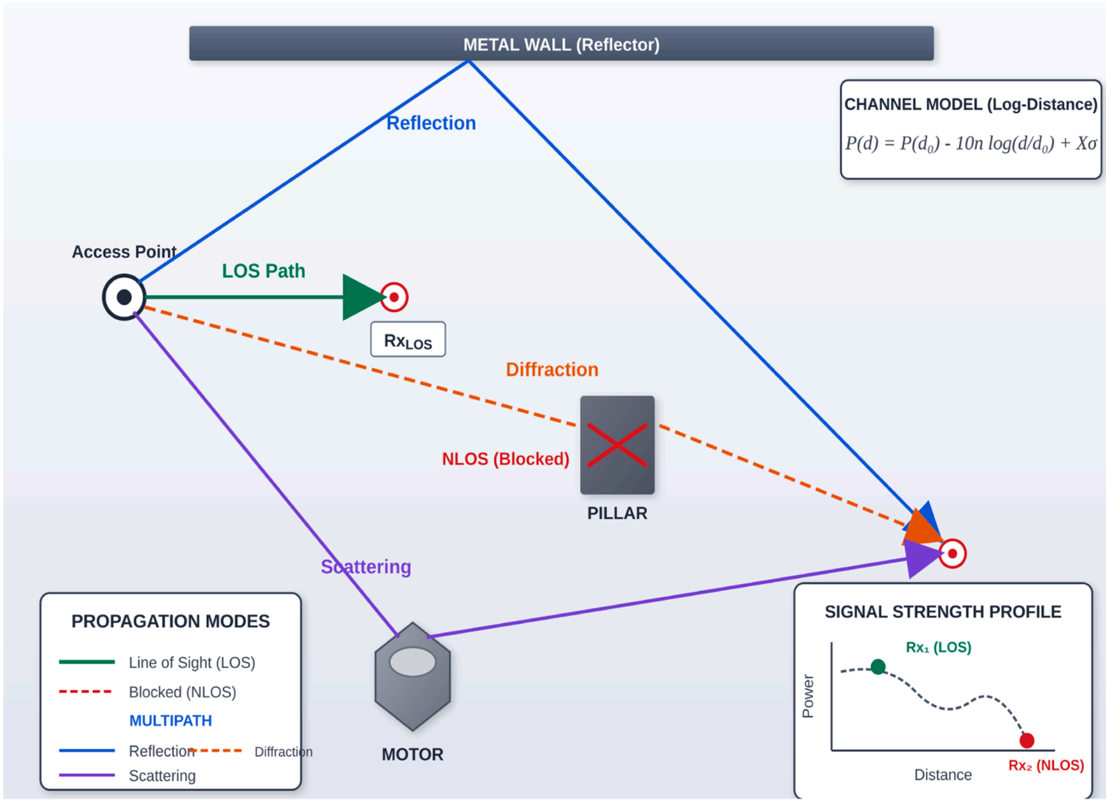

Fig. 8. Indoor propagation physics.

relatively long range and good penetration through obstacles such as walls, making it suitable for broad coverage across indoor facilities. However, this band is heavily congested due to the large number of devices operating within it, which can lead to interference and reduced reliability [49]. The 5 GHz band, also used for Wi-Fi, supports higher data rates and experiences less congestion compared to 2.4 GHz. Its main limitations are a shorter effective range and reduced penetration through obstacles [34].

UWB technology has emerged as a promising solution for indoor positioning, offering the potential for high accuracy, often achieving centimetre-level precision. This high accuracy is primarily attributed to its large bandwidth, typically spanning from 3.1 GHz to 10.6 GHz. UWB signals are characterized by their robustness to multipath fading due to the use of very short pulses. mmWave frequencies provide extremely large bandwidths, enabling very high data rates and the potential for highly precise positioning [39]. Millimeter-wave technology, operating in the 30–300 GHz frequency range, offers distinctive characteristics that make it highly relevant to indoor positioning environments. The vast bandwidth available at these frequencies enables not only ultra-high data rates but also fine-grained positioning accuracy. Nevertheless, mmWave signals are limited in range and are highly susceptible to blockage by obstacles, which can pose challenges in complex indoor environments [48].

The choice of frequency band for an IPS should therefore be guided by the specific application requirements, the size and layout of the facility, the density of obstacles, and the desired balance between coverage, accuracy, and data throughput. Higher frequencies generally offer greater bandwidth and, consequently, higher positioning precision, but at the cost of coverage and obstacle penetration. Conversely, lower frequencies provide better coverage and penetration but may suffer from congestion and limited data rates.

The fundamental engineering trade-off centres on the relationship between penetration capability and timing resolution, wherein lower frequencies penetrate obstacles more effectively but require physically larger antennas and offer reduced temporal resolution, while higher frequencies enable compact antenna designs and precise Time-of-Flight measurements but suffer greater path loss and increased sensitivity to NLOS conditions. Fig. 9 compares indoor positioning performance across different frequency bands.

4.4. Directivity and gain

In IPS, achieving sufficient antenna gain is critical to compensating for path loss, which refers to the reduction in radio wave power density as it propagates through space. Path loss can be particularly pronounced in indoor environments due to the presence of obstacles such as machinery, walls, stored materials, and potential interference from other electronic devices [64] . High-gain directional antennas can improve IPS performance by extending coverage and reducing interference, as they focus transmitted or received energy along specific directions [24]. The required antenna gain is determined by factors including the desired coverage area, the sensitivity of the receiver, and the anticipated signal attenuation in the indoor environment [92]. Enhancing transmit power at the antenna interface can be achieved either by increasing the transmitter's output power or by selecting an antenna with higher gain than the typical dipole-like designs commonly used in indoor localization systems [44].

Furthermore, directivity, which is the property of concentrating radiated power into a narrow beam, allows the system to spatially filter out unwanted signals and reflections [43]. This is particularly effective in reducing the impact of multipath interference, where signals arrive at the receiver via multiple paths (e.g., reflections off walls), which is a major source of error in indoor environments [47,93]. Highly directional antennas, such as those used in phased arrays or smart antenna systems, can be steered to track a target, effectively isolating the dominant LOS path and suppressing interfering signals from other directions, thereby improving ranging accuracy and overall positioning precision [94]. For instance, [95], a high-gain tapered-slot antenna

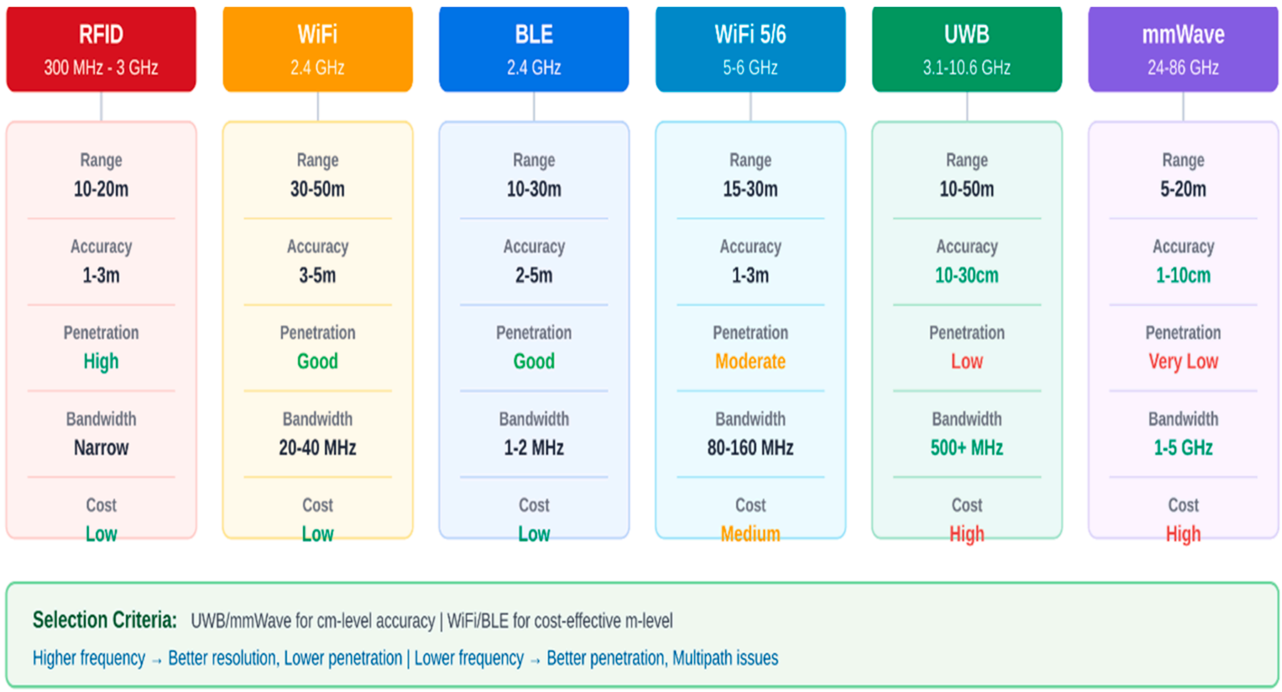

Fig. 9. Indoor positioning technologies and their corresponding bands.

(TSA) for 2D indoor wireless positioning incorporates three square slots in the radiating element and a semi-circular feature at the tapered aperture edge to enhance directivity while remaining compact. The fabricated TSA achieves a peak realized gain of 8.92 dBi at 9 GHz (7.06–8.55 dBi across 5–9 GHz) and exhibits narrow 3-dB beamwidths; its superior directivity concentrates the main lobe on boresight and suppresses back lobes, reducing energy dispersion. The system produced 2D localization errors of 3.27–16.33 cm in a 4 × 4 m test area, demonstrating that the gain and directivity improvements materially enhance indoor positioning accuracy while preserving a small footprint. In [92],the authors designed a directional circularly polarized UWB patch antenna (6.5 dBi gain, 8 dBi directivity, 180° coverage) to replace conventional omnidirectional linearly polarized monopoles in real-time locating systems. Experimental measurements demonstrate ~100 m increased reading range (175 m vs. 82 m), orientation-independent received power regardless of tag-reader antenna alignment and effective multipath mitigation through circular polarization. The work shows that optimizing antenna gain and directivity can substantially improve positioning performance without requiring hardware modifications to existing commercial systems. The design of array antennas for indoor positioning enables further directivity and gain enhancement through the combination of multiple radiating elements.

A narrow beam steering antenna array operates at 2.45 GHz with four dipole-Yagi elements integrated via 4 × 4 Butler matrix, achieving peak gains of 9.1–9.8 dBi and narrow 21.5°–24.5° beamwidth for enhanced directivity in the sweep plane is presented in [94]. The antenna's high directivity effectively minimizes multipath through narrow fan beam radiation, achieving superior localization accuracies of 1.64 m (trilateration), 1.07 m (triangulation), and 0.7 m (fingerprinting). The 9+ dBi gain and narrow beamwidth significantly outperform omnidirectional systems by concentrating radiated power directionally while rejecting reflections from floors and ceilings. In [96], a liquid-crystal reflectarray steered-beam antenna delivering ≈25 dB boresight gain is proposed; measured and simulated results show that its high gain and tight directivity increase the SINR of specular multipath, suppress diffuse clutter, and substantially reduce the position error bound in LOS scenarios. The work presents a practical, electronically reconfigurable high-gain solution for multipath-assisted indoor positioning and quantifies how directivity improves ranging performance—at the expense of reduced angular coverage and greater demands on beam steering and orientation management.

4.5. Radiation pattern and radiation efficiency

The radiation pattern of an antenna, which describes the spatial distribution of the power radiated by the antenna, is equally important in IPS. A well-designed radiation pattern ensures adequate coverage within the intended indoor environment [97,98].

Traditionally, positioning systems rely on omnidirectional antennas that receive from all azimuth directions, but this broad coverage often degrades localization accuracy, increases processing load, and raises the risk of network congestion [24,94]. In indoor settings, they remain useful because they provide relatively uniform coverage, reduce dead zones, and maintain links to tags moving unpredictably [99]. In RSS-based lateration, for example, antennas should ideally exhibit perfectly isotropic 3D radiation for homogeneous signal propagation; since truly isotropic radiators cannot be built, toroidal patterns with omnidirectional azimuth coverage and controlled elevation directivity are adopted instead [100] . However, their lack of spatial selectivity limits angular resolution Conversely, AoA systems benefit substantially from narrow beamwidth patterns that provide higher angular resolution enabling more precise angle estimation [94] . The directional radiation patterns facilitate distinguishing direct path signals from multipath components, thereby improving detection reliability of the true first-arriving signal essential for accurate ToA extraction [101].In [102], the authors demonstrated through numerical double-directional channel simulations that combining narrow-beam directional antennas with circular polarization substantially reduces the multipath-to-LOS power ratio in indoor ToA-based systems—especially for ceiling and floor reflections—thus improving delay estimation in bandwidth-limited positioning scenarios.

There is often a trade-off between antenna gain and the radiation pattern. High-gain antennas typically achieve their gain by focusing the radiated power into a narrow beam, which can provide strong signal strength in a specific direction but might result in limited coverage area [23]. Conversely, lower-gain omnidirectional antennas provide broader coverage by radiating power in almost all directions but might offer weaker signal strength in any direction. In [103], Dashti et al. showed, through numerical post-processing of measured indoor UWB channels, that appropriately oriented directional transmit antennas can reduce ToA ranging error variance compared with omnidirectional elements, indicating that antenna radiation patterns have a substantial influence on ranging accuracy in multipath environments .Using virtual-array synthesis of azimuthal patterns, they demonstrate that steering the main lobe toward the receiver lowers the relative contribution of off-axis multipath while preserving the LOS component, which yields a more reliable detection of the first-arriving path required for accurate ToA estimation.

Radiation efficiency measures how effectively an antenna converts the electrical power accepted at its input terminals into radiated electromagnetic power. The power that is not radiated is lost as heat, primarily due to conductor losses in the antenna's metal and dielectric losses in its substrate. High radiation efficiency is crucial for all antennas but is especially critical for low-power and battery-operated devices like BLE beacons, active RFID tags, and other IoT sensors [104]. For these devices, every milliwatt of power is precious, and an efficient antenna ensures the maximum possible range for a given battery life. In UWB systems, which operate under strict low-power spectral density masks, high efficiency is also vital to maximize the signal-to-noise ratio at the receiver. The radiation efficiency of an antenna is determined by its geometry and structure. The antenna low efficiency has a direct and detrimental impact on the performance of an indoor positioning system. A weak radiated signal from the antenna will result in a low SNR at the receiver, which can be a mobile device or a tag. A low SNR makes it difficult to accurately measure signal parameters such as the AoA or RSS, which are crucial for determining the position of the target [105]. The increased susceptibility to noise and interference in a low-SNR environment leads to larger errors in position estimation, ultimately degrading the accuracy and reliability of the entire positioning system.

4.6. Polarization

Antenna polarisation describes the orientation of the electric field of the radiated electromagnetic wave. Polarisation may be linear, where the electric field oscillates along a fixed straight line (either vertical or horizontal), or circular, where the electric field vector rotates continuously as the wave propagates (either right-hand or left-hand). In indoor positioning systems, matching the polarization of the transmitting and receiving antennas is necessary for efficient power transfer and minimal signal loss. The estimated range between anchor and tag is also affected by tag orientation, because the antenna-related time delay varies with orientation and should be kept as small as possible to preserve positioning accuracy. A 1 ns change in time delay corresponds to a range error of about 30 cm, and the largest delays typically occur when the tag and anchor antennas are cross-polarized [106].

The two primary types of polarization are linear and circular, as shown in Fig. 10. The choice between linear and circular polarization can significantly impact the performance of an IPS, especially in dynamic indoor environments where the orientation of tracked objects might vary unpredictably. Linear polarization is most effective in controlled indoor environments where the tag or mobile unit maintains a stable and predictable orientation, and the link between reader and tag remains largely unobstructed. Under such conditions, as indicated in [107], a linearly polarized reader can direct its energy more deliberately, producing a concentrated electromagnetic field that improves range and penetration. When the tag's orientation is assured, this focused field becomes an advantage, enabling more reliable coupling and extended coverage. For this reason, linear polarization continues to be used in tightly regulated indoor settings, despite its susceptibility to performance loss when the tag rotates or departs from the expected alignment [23].

In indoor environments with numerous metallic surfaces and obstacles, the signals used for positioning can experience multiple reflections, leading to a mix of polarization states at the receiver [108].

To mitigate the effects of polarization mismatch caused by reflections in indoor environments, circularly polarized antennas are often employed [43]. These antennas are less sensitive to the orientation of the incoming signal and can effectively receive both vertically and horizontally polarized components of the reflected waves. The ability of circularly polarized antennas to capture signals regardless of their orientation after multiple reflections often results in better overall performance in multipath-rich indoor environments.

The choice of antenna polarization therefore remains a major design consideration for IPS systems, ensuring robust and accurate localization despite challenging propagation conditions. Published studies have investigated several compact CP antennas designs for UWB, Wi-Fi, and RFID positioning systems [109–111].

To further enhance robustness against polarization mismatch and multipath fading, dual-polarized antennas and polarization diversity techniques are employed. A dual-polarized antenna integrates two orthogonal polarizations (e.g., vertical and horizontal) into a single physical unit, allowing the system to simultaneously transmit or receive signals on both polarizations [26,107] . This approach effectively doubles the information captured from the channel. Polarization diversity is a form of spatial diversity where the receiver selects the strongest signal from two or more orthogonally polarized antennas.

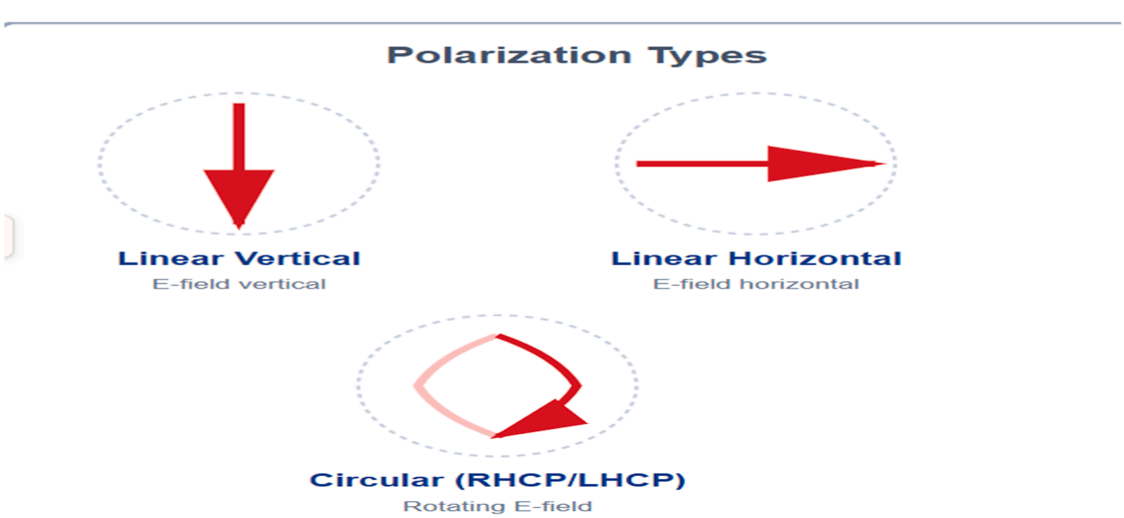

Fig. 10. Linear and circular polarizations of antenna.

4.7. Bandwidth

The bandwidth requirements for indoor positioning antennas depend fundamentally on the localization technique employed. Timing-based methods such as ToA and TDoA exploit wide bandwidth to achieve improved temporal resolution [5,87], while RSS techniques derive no benefit from large bandwidth, as signal strength is an inherently narrowband parameter unrelated to pulse timing characteristics [23].

UWB systems exemplify the timing-based approach, requiring bandwidths spanning hundreds of megahertz to several gigahertz to maximise range resolution and distinguish line-of-sight signals from multipath reflections [19]. An additional advantage of spreading information across wide frequency ranges is that transmit power can remain low, permitting indoor deployment without interference to nearby devices.

For BLE-based positioning, bandwidth constraints are even more pronounced. BLE operates with only 2 MHz channel bandwidth, fundamentally limiting timing-based approaches .In [112], an experimental comparison of BLE- and UWB-based direction-finding using commercial AoA hardware showed that UWB consistently achieved sub-10° mean angular errors in both LOS and obstructed-LOS conditions, while BLE frequently exhibited errors above 20° in the presence of multipath, human blockage, and interference. The authors concluded that UWB is inherently better suited for high-precision short-range direction finding. Consequently, most BLE positioning systems rely on RSS fingerprinting or AoA techniques rather than timing-based methods [45]. The advantage of wide-bandwidth over narrowband operation in time-based positioning systems is further confirmed in [68], where a hybrid UHF/UWB planar antenna incorporating a high-bandwidth UWB element (3.1–10.6 GHz) with VSWR below 2 and 95% pulse fidelity attained approximately 2 cm ToA-based positioning accuracy, whereas narrowband RSS-based RFID methods operating on the same platform achieved only 1 m accuracy owing to environmental variability and orientation sensitivity.

In contrast, narrowband antennas may be sufficient for certain Wi-Fi, BLE, or RFID applications, depending on the intended use case and performance objectives [23]. In RFID systems specifically, narrow antenna bandwidth proves advantageous, as it filters out-of-band interference and yields a higher quality factor, thereby improving overall system performance. For example, in [113], an RFID reader antenna in the form of a compact 1 × 2 slotted microstrip patch array at 2.45 GHz is proposed, using a defected ground plane to improve matching and efficiency while maintaining a directional main beam. The design is deliberately narrowband, with roughly 80 MHz −10 dB bandwidth, to align with allocated RFID channels and provide higher Q and out-of-band rejection for RSS/ToF-style indoor positioning rather than UWB-grade time resolution. mmWave systems leverage extremely wide bandwidths for high-precision positioning. In [114], Wang et al. theoretically analysed a 60 GHz mmWave localization network with a mobile massive, phased array and up to 2 GHz bandwidth, showing via Cramér–Rao bounds that such beamformed ultra-wideband operation enables millimetre-level 3D ranging accuracy. However, mmWave antennas face unique design challenges, including increased path loss and sensitivity to blockage, which must be addressed through careful antenna design and beamforming strategies.

Regardless of technique, antenna bandwidth must be carefully matched to system requirements, as insufficient bandwidth can limit data rates and degrade ranging accuracy in timing-dependent methods.

4.8. Beamwidth and beam steering capability

Beamwidth is defined as the angular width of an antenna's main radiation lobe where the signal strength is at least half of the peak power (the −3 dB point). It determines angular coverage and resolution; in IPS, narrow beams improve signal-to-noise ratio along known paths but require careful aiming or electronic steering [23].

A narrow beamwidth corresponds to high gain and directivity, allowing the system to focus energy precisely and resolve the angle of arrival more accurately [94]. This directional focus is advantageous for long-range, point-to-point communication and controls how many multipath components enter the system, as a narrower beam naturally suppresses unwanted reflections [94] . Achieving very narrow beams, however, is difficult without large antenna arrays. The situation becomes more demanding when the direction of the transmitter is unknown, since a narrow main lobe must be steered across the entire azimuth—electronically or mechanically—adding complexity and cost [115]. Conversely, a wider beamwidth provides broader coverage, making it suitable for general-purpose networks [116]. The trade-off between beamwidth and coverage is a key design decision for IPS, and a successful system may require dense deployment of antenna or a hybrid approach that combines omnidirectional antennas for broad coverage with highly directional antennas for high-precision zones.

Beam steering addresses the challenge of directing narrow beams toward targets of interest. It refers to the ability to change the direction of the main lobe without physically moving the antenna, a capability relevant to advanced systems such as mmWave and AoA-based localization [117]. Beam steering is typically achieved using an antenna array in which the phase of the signal fed to each element is electronically controlled [93]. By adjusting these phases, individual signals add constructively in a desired direction and destructively in others, allowing a fixed anchor to track a moving target, mitigate interference from specific directions, and exploit different spatial channels to combat multipath.

A range of beam-steering architectures have been reported, including electronically scanned monopulse structures [115–118], switched-beam antennas [93]and electronically steerable parasitic array radiator (ESPAR) antennas [119–121] . These architectures require dedicated hardware and control circuitry to generate or switch directive beams across a target angular field of view. More recently, leaky-wave antennas (LWAs) have attracted attention as a compact, low-cost alternative for angle-of-arrival estimation based on RSS measurements [51,122]. In LWAs, beam steering arises naturally from the leaky-wave dispersion profile, enabling direct interfacing with arrival signal without complex scanning hardware.

4.9. Feeding techniques

In antenna design, the feeding method used to excite the structure is a critical factor, as it directly influences BW, radiation efficiency, and fabrication complexity. Below is an overview of common feeding techniques:

- Coaxial feed: This straightforward method delivers the signal directly to the patch antenna. The inner conductor of the coaxial probe connects to the metallic patch, while the outer conductor is grounded. To minimize unwanted mutual coupling, a feeding network on a dedicated layer often incorporates a grounded coplanar waveguide (GCPW) connected to the coaxial probe. Coaxial feeding is widely used due to its low cost, effective impedance matching, and reduced spurious radiation. However, it typically offers a narrower bandwidth compared to other methods [123].
- Microstrip feed line: In this approach, a microstrip line is directly connected to the patch via an inset etched at the patch edge to match the feed line impedance with the patch's input impedance. This technique is simple to model and fabricate, making it a popular choice in low-cost designs. Its main limitations arise with thicker substrates intended to enhance bandwidth, where surface-wave excitation can increase spurious radiation and reduce effective bandwidth [123,124] . Additionally, higher cross-polarization makes microstrip feeding less suitable for DoA applications, where polarization purity is critical.

- Aperture coupling: This technique employs two substrates separated by a ground plane containing a slot. A microstrip line on the lower substrate feeds the patch through the aperture. Using a high-dielectric lower substrate and a low-dielectric upper substrate enhances radiation efficiency, while the ground plane minimizes spurious radiation [124].
- Proximity coupling: Here, the microstrip feed line is placed between two dielectric substrates, with the radiating patch located on the top of the upper substrate. This configuration prevents spurious radiation by eliminating direct contact between the feed line and patch and improves bandwidth by up to 13%, although it increases fabrication complexity and cost [123].

Coaxial and microstrip feeding techniques allow relatively straightforward impedance matching by adjusting the feed position and size. They offer acceptable spurious radiation and bandwidth but can introduce asymmetries that excite higher-order modes, leading to unwanted cross-polarization. Aperture and proximity coupling methods address these limitations, providing better isolation and bandwidth at the expense of more complex fabrication [125].

In practical indoor positioning systems, antenna implementation is often constrained by the complexity of the feeding network. System performance depends heavily on both the quality of the input signal and the precision of received signal interpretation. For instance, in LWA antennas used for positioning, the feeding network must deliver a stable, well-defined signal over a wide bandwidth—a challenging requirement in practice [126] . Furthermore, precise control of signal frequency is essential for beam steering, necessitating high-performance frequency synthesizers. In multi-beam or electronically antennas, feeding networks become even more complex, requiring multiple input ports or sophisticated beamforming networks to effectively control the radiation pattern.

4.10. Practical antenna performance metrics for indoor positioning

Beyond the conventional antenna parameters discussed above, several practical factors directly affect positioning performance in real indoor environments. For angle-based methods such as AoA, phase-centre stability is a particularly important consideration. In practice, the phase centre shifts with frequency, angle of incidence, and environmental conditions, which distorts the effective array geometry and introduces systematic angular errors that are easily mistaken for true changes in arrival direction — a problem that becomes especially significant in wideband UWB and compact array implementations [127]. For time-based techniques, including ToA, TDoA, and RTT, the focus shifts to group-delay behaviour. Since the antenna contributes to the overall signal path, frequency-dependent delay distorts the received waveform and shifts the estimated arrival time; and given that EM waves travel at roughly 30 cm/ns in free space, even small delay variations can lead to noticeable ranging errors [88,128] . Ensuring low and stable group delay, alongside proper antenna delay calibration, is therefore essential for achieving centimetre-level accuracy in UWB systems.

Orientation and polarisation sensitivity introduce an additional layer of complexity, particularly in realistic deployments where device position is not controlled [20]. In RSS-based positioning, changes in orientation and polarisation alignment can cause large fluctuations in received power, often exceeding distance-related variations, while body shadowing further amplifies this effect in wearable scenarios [129]. At higher frequencies, such as in millimetre-wave (mmWave) systems, beam-training overhead becomes a key practical constraint [130]. Although narrow beams enable fine angular resolution, aligning transmitter and receiver beams requires sweeping the entire codebook, introducing latency that limits the achievable update rate [131]. While position-aided beam prediction can significantly reduce this overhead, real-world GPS inaccuracies and multipath effects substantially degrade prediction performance in practice [132]. Taken together, these factors are integral to overall system performance and deserve consideration alongside conventional antenna parameters when evaluating and designing indoor IPS.

5. State-of-the-art antennas for indoor positioning

The selection of antenna type is a key factor that directly affects the performance of indoor positioning systems and applications. This section presents an overview of the main antenna types used in indoor localization, together with a literature survey for each category.

5.1. Dipole antennas

Dipole antennas are characterized by a relatively omnidirectional radiation pattern in the horizontal plane, making them well-suited for providing broad coverage. They are commonly used in basic RSS-based localization systems due to their simplicity and low cost, and they can also function as individual elements within more complex antenna arrays [133].

In IPS, dipole antennas are often employed in scenarios where a simple and inexpensive solution is sufficient for general tracking or coverage—for example, in basic Wi-Fi or BLE beacon deployments for proximity detection. However, dipole antennas have inherent limitations in terms of gain, which can restrict the effective range of the system. They are also more susceptible to interference, particularly in the electromagnetically noisy environments typical of indoor facilities. While dipole antennas provide a straightforward and cost-effective option, their constraints in gain and interference rejection must be carefully considered when designing IPS solutions, especially in applications with stringent performance requirements.

To address these limitations, researchers have developed advanced antenna dipole configurations. For example, in [134] a compact, dual-band tag antenna is presented that integrates elliptical dipole elements (2.9–5.35 GHz) with U-shaped PIFA structures for UHF operation (881–913 MHz). This miniaturized design uses differential feeding and inductive loading to achieve a 59.5% impedance bandwidth and port isolation exceeding 20 dB, providing directional radiation characteristics beneficial for accurate indoor localization.

To achieve a compact, low-profile, high-gain radiator with wide elevation coverage for wall-mounted readers, the authors in [135] used printed dipole–Yagi elements. The design produces narrow azimuth beams ($\approx 12^\circ$), broad elevation coverage (50°–120°), measured array gains of 7.8–11 dBi, and roughly 80% efficiency—features that meaningfully improve localization accuracy and lower access-point density. These gains come with the trade-off of a larger element footprint and more involved feeding and matching. Similarly, the authors of [136] proposed a quasi-Yagi antenna for indoor location tracking employing parasitic directors adjacent to the dipole element, as shown in Fig. 11(a) and (b). The dipole achieves 6.46 dBi maximum gain at 8 GHz with 4.36 GHz bandwidth (5.03–9.39 GHz) and excellent directional characteristics. Integrated with UWB radar, the antenna successfully tracks targets within 1–4 meters with 0.2405 m root mean square error, demonstrating the dipole-director configuration's effectiveness for precise indoor positioning in a compact 32.7×33 mm form factor.

For high-precision AoA estimation, a compact null steering antenna with two dipole antennas and parasitic reflector elements at 2.45 GHz for is presented in [133].The parasitic elements stabilize null depth during phase scanning, achieving approximately 40 dB null depths from -60° to 60° with measured improvements of 14.5–15.8 dB compared to the antenna without parasitic elements. Cross-polarization remains under -25 dB. The null steering approach enables robust angle-of-arrival estimation for indoor real-time location systems. Another approach to utilizing dipoles for indoor tracking is presented in [116], employing an electrically small, circularly polarized hybrid magnetic dipole antenna that addresses polarization mismatch and multipath fading. The design achieves a 104° half-power beamwidth and 4.57 dBi peak gain within a compact $0.12\lambda \times 0.12\lambda \times 0.04\lambda$ footprint

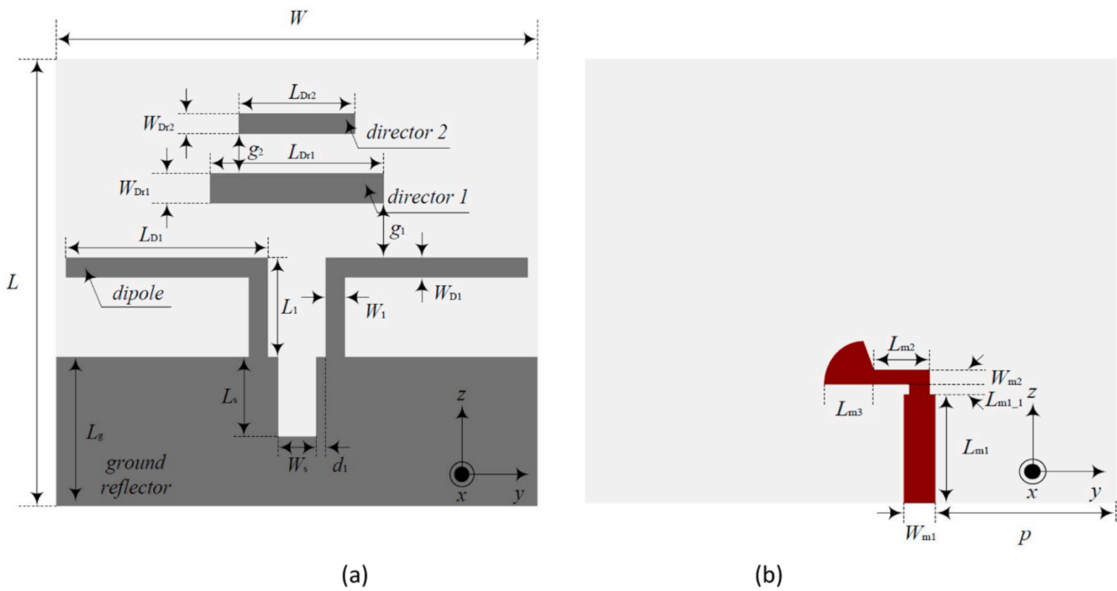

Fig. 11. Published Dipole Yagi antenna: (a) top layer, and (b) bottom layer [136].

across the 902–928 MHz UHF band, demonstrating that orthogonal magnetic dipole topologies enhance coverage and reliability for RFID and IoT localization systems. Fig. 12(a) and (b) present the top and bottom views of the fabricated proposed antenna, while Fig. 12(c) and (d) display the perspective view and measurement setup in a near-field chamber, respectively.

5.2. Microstrip patch and array antennas

Microstrip patch antennas have become popular in IoT applications for indoor positioning systems in indoor environments, owing to their compact form factor, ease of integration, and predictable radiation characteristics [137]. 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 IPS applications have focused on achieving broad bandwidth operation to support multiple positioning techniques simultaneously, including UWB ranging [138,139]. For instance, a directional UWB patch antenna system developed in [92] replaces conventional omnidirectional dipole-like antennas in real-time indoor locating systems. The design employs capacitive feeding and a coupler, as shown in Fig. 13, to realize wideband circular polarization with 180° coverage, achieving a stable 6 dBi gain. Measurements demonstrated nearly 100 m range improvement, consistent received power across tag orientations, and significant multipath suppression compared to commercial omnidirectional dipoles, thereby enhancing indoor positioning robustness without hardware modification. However, this improvement comes at the trade-off of reduced angular coverage, as the 180° radiation pattern limits flexibility

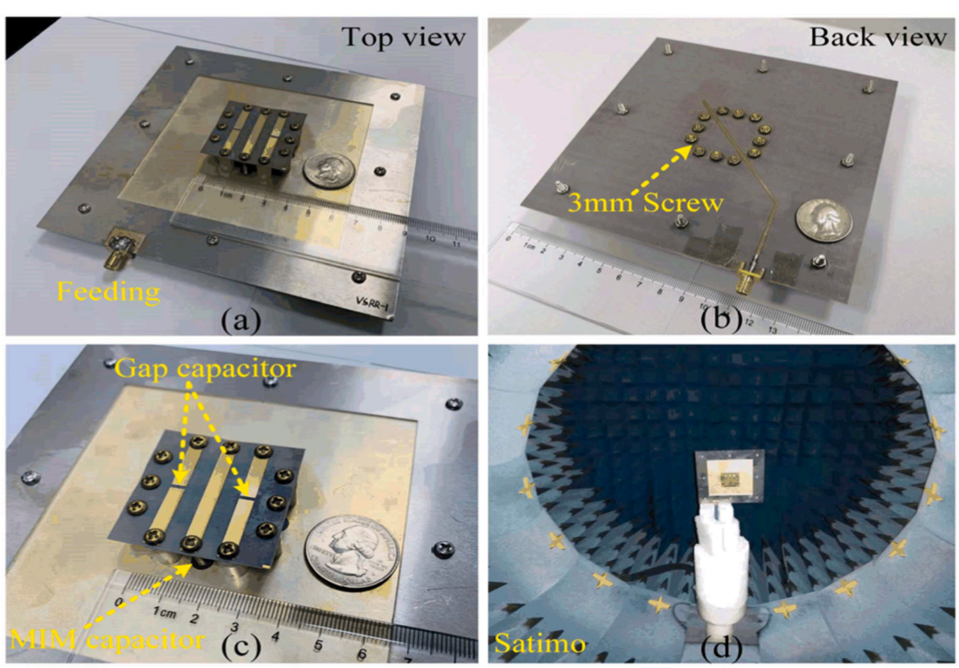

Fig. 12. Published fabricated antenna. (a) Top view, (b) bottom view, (c) perspective view, and (d) measurement setup in a near-field chamber [116].

Fig. 13. Prototype of the published patch antenna operating over UWB [92].

in scenarios requiring full 360° detection. Similarly, a tripod-shaped single-radiator Similarly, a tripod shaped patch antenna is presented in [140] substitutes conventional multi-element arrays for direction finding in compact devices. The design employs a tripod radiator with three edge-fed ports and an optimized quadratic edge profile refined by a genetic algorithm to secure wideband operation from 5.8 to 11.9 GHz and a peak gain of 3.5 dBi. Measurements of direction-of-arrival estimation using DW3000-derived CIR data yield root-mean-square angular errors of 1.57° at a test distance of 30 cm and 4.58° at 60 cm, confirming the antenna's suitability for UWB direction-finding in space-constrained smart devices.

In [141], a compact patch-monopole antenna is introduced that prioritizes wide instantaneous bandwidth, omnidirectional radiation, and a PCB-friendly low profile. The design modifies a hexagonal radiator into a concave/oval form, implements a CPWG with vias to suppress non-radiating transmission-line effects, and incorporates a ribbon-shaped slot to extend the band. Measurements of the prototype show omnidirectional radiation patterns, a peak gain of ≈4.1 dBi, and favourable group-delay and system-fidelity metrics—demonstrating a practical patch-antenna solution for reliable indoor UWB positioning.

In patch antenna design, 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 [142].

Array antennas, which consist of multiple individual antenna elements combined in a specific configuration, are widely used in IPS to achieve enhanced performance in terms of radiation pattern, gain, and beam steering. Phased arrays are a type of array antenna where the phase of the signal fed to each element is controlled to electronically steer the main beam of the antenna without physical movement [143]. This capability is particularly valuable for applications requiring dynamic adjustment of coverage areas or for rapidly scanning an environment to locate targets. Array antennas are crucial for advanced localization techniques like AoA estimation, where the precise

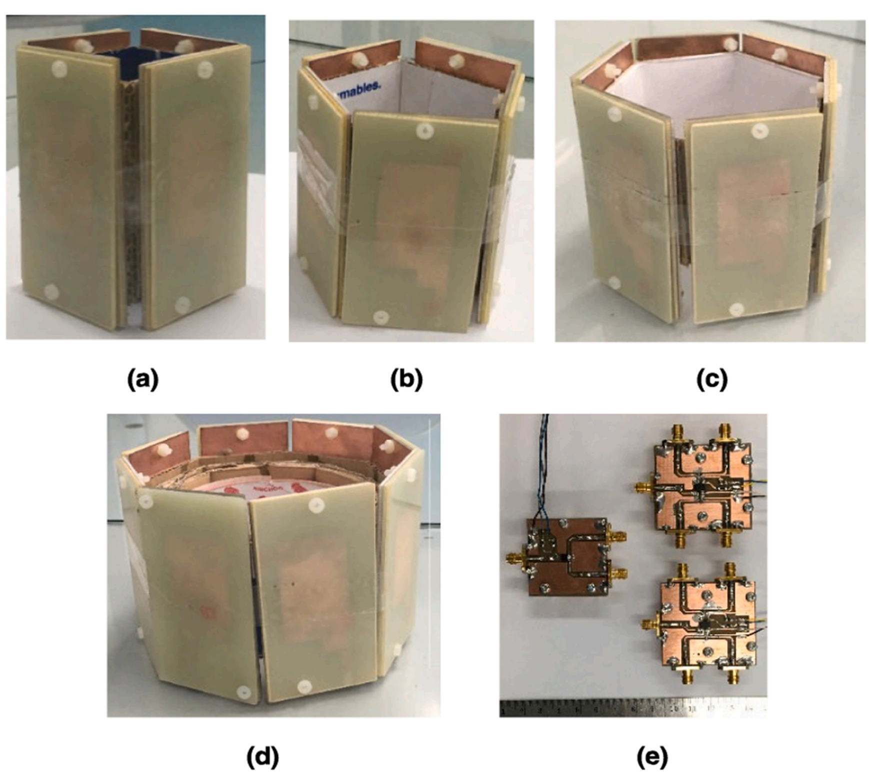

Fig. 14. Published circular array antennas and RF switch network: (a) four, (b) five, (c) six, (d) eight elements, (e) RF switch network [146].

measurement of the angle of signal arrival is determined by analysing the phase differences across the array elements [144] . In IPS, array antennas offer the potential for increased coverage, higher accuracy, and improved mitigation of multipath effects and interference. For instance, in a dynamic setting, phased arrays could be used to track the precise location of robots and autonomous vehicles in real time, adjusting the beams to follow their movement [145].

In [146], the researchers designed low-cost 4–8 element switched-beam circular microstrip patch arrays at 2.4–2.5 GHz, as shown in Fig. 14, to act as single-anchor Wi-Fi nodes for AoA-based indoor positioning without the complexity of fully adaptive arrays; a MEMS switch sequentially selects fixed beams while MUSIC and RSS estimate direction and distance, with the 8-element array giving the most uniform 360° coverage and best localization performance, though tests are limited to short-range 2D LOS-like indoor scenarios.

The increased deployment of autonomous vehicles in indoor environments has created a demand for precise localization. Because mobile units can move with many degrees of freedom, antenna arrays with wide angular coverage, preferably approaching hemispherical, are required. In designing such arrays, a trade-off arises between the targeted localization accuracy and the number of antenna elements. Furthermore, as several reference nodes with more limited angular coverage are typically needed to span the localization area, the total number of elements should be minimized to constrain system cost and power consumption [147,148] .In [148], the authors optimized two sparse eight-element planar patch receive arrays at 24 GHz, as shown in Fig. 15, for a SIMO FMCW radar using 3D AoA-based indoor positioning. Multi-objective particle swarm optimization was applied to balance main-beam width and sidelobe level under $\lambda/2$ spacing and low-cost constraints, achieving ambiguity-free scanning up to about $\pm 60^\circ$ and angle errors around 1° in a foyer and below $\approx 2.6^\circ$ in a multipath corridor. The results demonstrate accurate 3D indoor positioning, although relatively high sidelobes (≈ -3 dB) still limit robustness in harsh corridor multipath.

In [149], a phased-array antenna system is proposed to enable passive indoor localization of a mobile unit without modifying existing infrastructure. The system extracts CIRs from SLS preambles, compares beam-pattern amplifications to estimate angles, and derives time-of-flight from CIR peaks, then fuses multi-AP measurements with a Kalman filter; this approach yields mean errors of 17.6 cm (6.5 cm with trajectory filtering) and sub-meter accuracy in all trials, demonstrating that beam-pattern-aware processing with phased arrays can deliver practical, high-resolution passive positioning using standard mmWave links Similarly, an indoor BLE AoA system developed in [150] uses a dual-channel circular array**—comprising 12 dual-polarized elements—to achieve wide angular coverage and single-base-station positioning. This reduces infrastructure requirements while maintaining angular resolution. The method applies FFT-based frequency-offset compensation and employs a MUSIC super-resolution AoA estimator, combined with** an SVD-enhanced strong-tracking Kalman filter, to mitigate multipath effects and stabilize the trajectory in dynamic**, NLOS** environments. Measurements report static errors typically within 0.3–0.6 m and sub-meter accuracy across the LOS coverage area, demonstrating that a carefully designed array and robust tracking can deliver high-accuracy indoor positioning with minimal antenna hardware.

In [151], the authors designed an electronically steered 3-element aperture-coupled microstrip array for passive UHF RFID indoor positioning, replacing mechanically rotated reader antennas. By phase-steering the array at 866 MHz over about $\pm 30^\circ$, the reader scans the beam, collects backscattered RSS from tags, and estimates their angle, then triangulates two such angle measurements to obtain 2D position (RFID technology, RSS/AoA-type method). Far-field tests report angular deviations below $\approx 1.6^\circ$ and lateral errors under ~ 4 cm at a few metres, but the system requires quasi-static tags, far-field conditions, and remains sensitive to multipath blind zones.

5.3. Multiple-input multiple-output (MIMO) antenna

MIMO antenna systems critically enhance both communication capacity and accuracy within IPS [21]. 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). The application of MIMO principles has extended beyond communication to significantly enhance positioning accuracy [21],[152]. Recent works have focused on developing MIMO antenna configurations and signal processing techniques that optimize spatial resolution and multipath exploitation rather than just data throughput [153,154].

In [155], a low-profile three-element circularly polarised UWB MIMO patch array for channel 9 (7.75–8.25 GHz) is proposed to enable RSS-based indoor positioning. The MIMO array, fed via a Wilkinson divider, achieves -10 dB bandwidth from 7.61–8.48 GHz, CP over 7–8.89 GHz, gains up to about 8 dBi, and isolation better than -22.5 dB, which gives it clear application potential in indoor positioning systems; however, its positioning performance is not validated in a complete end-to-end localization setup. In [156], a compact multimode MIMO antenna is developed for AoA estimation in space-limited IoT devices achieved a full 360° field of view with angular errors under 0.1°, as shown in Fig. 16. This design reduces 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.

To enable high-precision AoA on size-constrained IoT devices

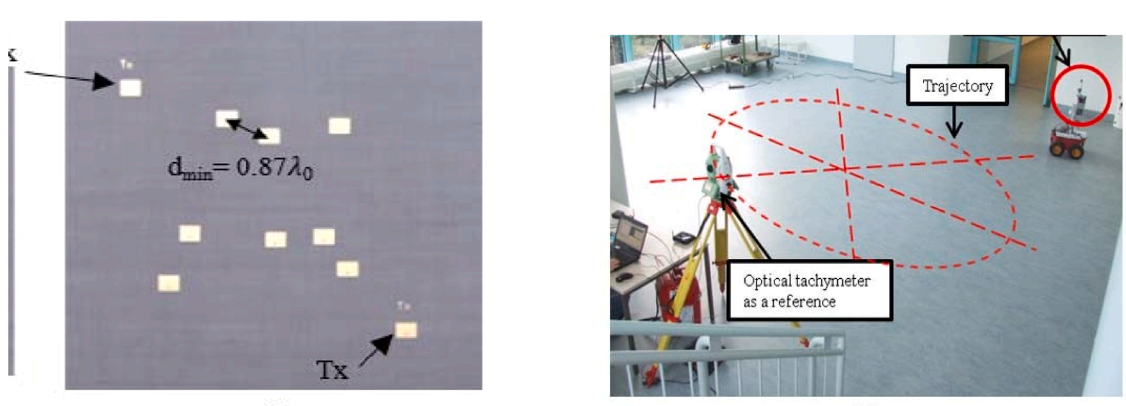

Fig. 15. Photographs of fabricated eight-element receiving arrays. (a) Optimized array (b) Measurement setup [148].

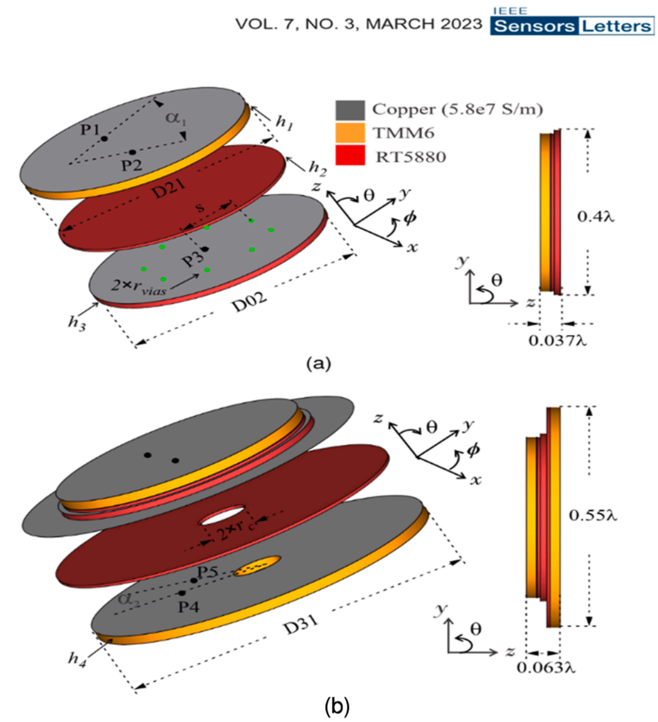

Fig. 16. MIMO antennas (a) Three-port MIMO design and (b) Five-port MIMO design [156].

without the aperture and coupling penalties of miniaturized arrays, the author in [157] develop a compact multimode MIMO radiator whose collocated ports excite orthogonal modes. Using full-wave port patterns and MUSIC processing, the five-port design achieves up to 75% size reduction versus linear arrays (≈40% versus circular arrays), 360° coverage, MAE $< 0.11^{\circ}$, and reliable multi-source separation, demonstrating array-comparable AoA performance in a much smaller form factor.

Massive MIMO systems present a promising approach to indoor localization, leveraging the high angular resolution capabilities of large-scale antenna arrays to overcome multipath propagation challenges. For instance, in [153] a massive MIMO system employing a 64-element uniform linear array is used together with a mixed-field sparse Bayesian learning algorithm to localize user equipment in both near-field and far-field conditions without requiring prior position information. Fig. 17 illustrates the indoor localization setup based on massive MIMO linear antenna arrays. Validation through real-time testing at 2.61 GHz demonstrates that this method achieves 49% improved localization accuracy with minimal data collection while maintaining robust performance under degraded signal conditions.

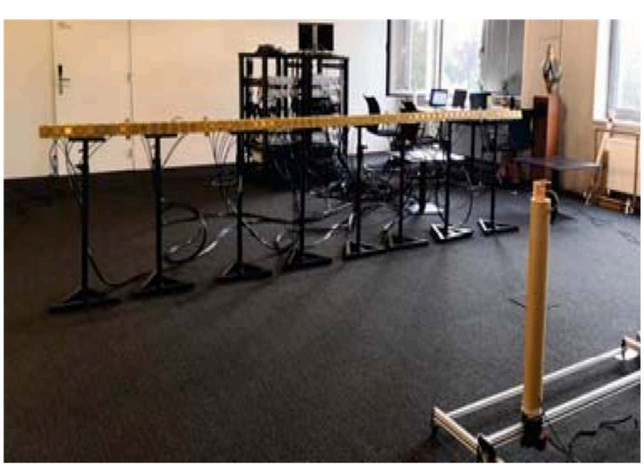

Fig. 17. Massive MIMO Linear antenna arrays with Indoor localization setup [153].

The need to integrate multiple antennas into small devices (e.g., asset tags, wearable sensors, mobile robots) for MIMO communication and positioning drives continuous research into compact antenna arrays. Key challenges include achieving high isolation between closely packed antenna elements, maintaining good radiation efficiency, and ensuring wideband performance. Recent advancements involve the use of innovative decoupling techniques, such as electromagnetic bandgap (EBG) structures [158], defected ground structures (DGS) [159], parasitic elements [160], and metamaterial-inspired isolators [161] . For instance, in [162] an eight-port UWB MIMO antenna leverages epsilon-negative metamaterial structures to achieve full UWB spectrum coverage (3.1–10.6 GHz) with high inter-port isolation, making it well suited for indoor localisation where wide bandwidth and spatial diversity improve signal reception in multipath environments. Superior MIMO metrics including envelope correlation coefficient below 0.0025 and total active reflection coefficient below −11 dB facilitate accurate positioning while supporting wireless connectivity in indoor applications.

5.4. Leaky-wave antenna (LWA)

A LWA antenna is a travelling-wave radiator that forms a directive, steerable beam from a single feed, thereby eliminating the bulky and lossy feeding networks associated with phased arrays. Its operation is governed by intrinsic frequency scanning: the main-beam direction is linked to the operating frequency, so beam steering is achieved solely by tuning frequency [163]. This dispersive behaviour makes LWAs well suited to indoor positioning, where a fixed, compact structure can illuminate different spatial sectors with high gain and thus enable accurate AoA or DoA estimation with reduced hardware complexity and cost. For example, passive frequency-scanned LWAs have been realised within the BLE advertising band (2.402–2.48 GHz) [164], where continuous beam steering across channels has been used to obtain high-resolution two--dimensional DoA estimates and to track moving IoT devices without active beam-scanning circuitry.

Several recent studies have focused on leveraging LWA for enhanced localization and direction-finding capabilities, often combining them with existing Wi-Fi techniques. For instance, [47] presents 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 RSS-based processing.

In [165]a single 2D localization system is developed, combing a dual port frequency scanned halfwidth microstrip leaky wave antenna with RSS based MUSIC processing for direction of arrival estimation and IEEE 802.11mc RTT ranging to determine smartphone position without CSI or active beam steering. This work demonstrates a low cost, calibration based RTLS achieving sub3 m accuracy using commodity hardware while enabling faster real-time tracking. A Wi-Fi direction finding system is developed in [166] that uses only two mechanically tilted 14 dBi LWA antennas, separated by 2 λ, to jointly apply CSI based phase difference interferometry and RSS based amplitude monopulse comparison. This combined approach suppresses the multiple DoA ambiguities and enables a 180° field of view with high angular sensitivity. The measurement tests show mean absolute errors down to 3.8° over 180°FoV (0.5° over ±45°), outperforming either method alone while avoiding extra antennas, active scanning, or multichannel operation.

Another approach to single-AP localization is presented in [167], where a 2D system combines a dual-port passive frequency scanning leaky wave antenna with a channel hopping RSSI acquisition scheme and a modified MUSIC algorithm for wide FoV DoA estimation. This hybrid amplitude-based DoA and RTT method achieved mean localization errors of 2.27 m indoors, extending the usable FoV threefold over prior monopulse designs while avoiding CSI access, active beamforming hardware, or multi-AP infrastructure.

Further advancement in passive beam scanning is demonstrated in [126], where a LWA system employs a bidirectionally fed half-width microstrip structure on a high-permittivity substrate to generate four frequency-steered directive beams. By pairing adjacent beams into three amplitude monopulse functions and applying an angular pseudospectrum method, it estimates tag AoA over a wide FoV of about 130°. Fig. 18 shows the experimental scenarios used in the indoor multipath measurements. Experiments in indoor multipath scenarios showed Root Mean Square Errors (RMSEs) as low as 3.7°, demonstrating a compact, low-cost alternative to phased arrays while enabling multi-tag detection with simple commodity hardware.

Focusing on compactness and planar design, a passive monopulse leaky wave antenna is developed in [168], employs a single bidirectionally fed halfwidth microstrip aperture to synthesize mirrored directive beams for amplitude comparison DoA estimation in W-iFi WLANs. the design achieves similar FoV (40°) and quasilinear monopulse response to a dual antenna tilted array, while remaining fully planar and more compact. Measurements reveal that its, yielding more stable monopulse patterns and lower nearfield angular error RMSE $\approx 2°$ beyond 1.5 m and $< 5°$ at 0.5 m thus improving shortrange localization without active scanning or phase measurements. In [130], a compact amplitude-monopulse antenna is employed, using two parallel air-filled leaky waveguides with extended bottom walls to synthesize four diagonally tilted beams, enabling joint two-dimensional direction finding in the 2.4 GHz ISM band. A 40° YZ-plane and 60° XZ-plane field of view is achieved for RSS-based DoA estimation, and accurate positioning with minimal errors is provided, advancing passive JRC systems for commercial Wi-Fi networks. Fig. 19 shows the LWA antenna connected to the Wi-Fi access point.

In [170], a null scanning leaky wave antenna (NSLWA) is developed. by employs a pair of specially engineered microstrip LWA elements with tailored broadside frequencies and a calibrated excitation phase offset to synthesize a frequency scanned radiation null along the scanning plane for mmWave direction finding. The design process formalizes null scanning synthesis theory, models and optimizes the two elements for matched beamwidths and gains and implements a feeding network with integrated phase shifter. Simulations and measurements show a deep, frequency steerable monopulse like null (≈ -48 dB at 35.5 GHz) whose scan matches the beams' crossover function, enabling spectral null type DF with potentially higher angular accuracy.

A bidirectional LWA system is presented in [171] employs a microstrip-based composite right/left-handed (CRLH) configuration

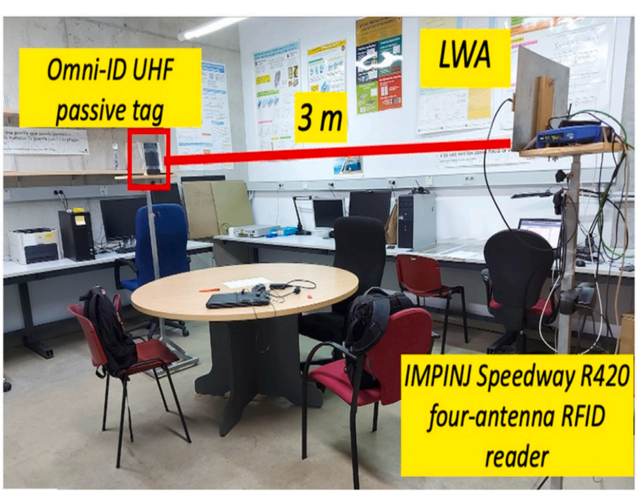

Fig. 18. Experimental scenarios of measurement in Indoor multipath experiment [126].

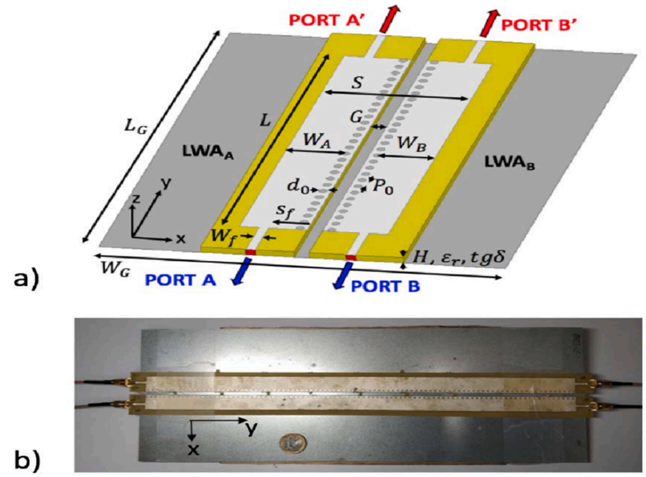

Fig. 19. Published LWA antenna (a) Scheme of LWA. (b) Fabricated prototype [169].

with periodically loaded series capacitors and shunt inductors to achieve continuous beam scanning from backward to forward quadrants. The leaky-wave aperture forms orthogonal scanning patterns, enabling two-dimensional AoA estimation using only received signal strength variations. Measurements demonstrate stable gain, low sidelobes, and sub-5° RMSE angular error in indoor positioning trials.

Another a dispersion-based LWA system is developed in [172] using two low-cost plug-in leaky-wave antennas to generate frequency-dispersed, orthogonally polarized signals for AoA estimation via spectrum analysis, enabling indoor Wi-Fi localization without sufficient LOS APs. A median localization error of 0.81 m is achieved—52 % lower than SpotFi alone—and SpotFi's error is reduced by 34 % when combined, providing a cost-effective enhancement for opportunistic Wi-Fi sensing in multipath environments.

A microstrip leaky-wave antenna (MLWA) system is proposed in [173] using a half-width, air-substrate design whose frequency-scanned main beam sweeps 70°–33° over 4.25–8 GHz, enabling simultaneous range and azimuth estimation in a single wideband sweep. Real-time 2D range–azimuth images are generated without mechanical scanning, and clear trajectory separation of two moving humans was achieved with $\sim$50 cm worst-case range resolution. In [174], a compact amplitude-monopulse LWA system is developed using a bidirectionally fed half-width microstrip LWA near broadside to synthesize sum and difference patterns over a 120° field of view. A low-angle, high-leakage synthesis enables 65 % radiation efficiency while high dynamic range is maintained. Accurate amplitude-only direction finding is demonstrated at 2.45 GHz, representing a compact wide-angle monopulse LWA for integrated IoT antenna-sensor applications.

A dual-port half-width microstrip leaky-wave antenna (HWM-LWA) system is developed in [18], in which frequency-scanned beams from opposite ports were used to estimate AoA via RSS and RTT-based ranging for full 2D localization. $\pm 40°$ beam steering per port enabled continuous $\pm 90°$ coverage. Sub-1.8° mean AoA and <0.8 m range errors were achieved, with 90 % of positions within 30 cm, representing the first integration of a frequency-scanned LWA with RTT for compact, wide-angle indoor positioning. Similarly, in [51], a frequency-scanned Bull's-Eye leaky-wave antenna (BE-LWA) is introduced, in which a concentric-ring PCB excites a cylindrical leaky mode to generate omnidirectional conical beams in backward (14–23 GHz, 130°FoV) and forward (23–32 GHz, 54°FoV. Dual-band operation enabled an 18 GHz sweep with MUSIC-based DoA RMSE of 1.31°, providing a thin, planar, passive wide-FoV solution for high-frequency localization.

Overall, frequency-scanned LWAs have emerged as compact and cost-effective alternatives to phased arrays for indoor localization, offering accurate two-dimensional DoA estimation and real-time tracking without active beamforming or multi-antenna infrastructures. Nonetheless, their current implementations are still constrained by limited FoV, calibration sensitivity, and dependence on simplified RSS-based methods, underscoring the need for more robust, wide-angle, and calibration-resilient architectures to meet the reliability and scalability requirements of practical IoT deployments.

5.5. Reconfigurable antennas

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 [117,175] . Several recent studies have focused on reconfigurable antennas, exploiting their pattern- and beam-agility to improve localization and direction-finding performance. For example, [146]introduce 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 [176], a circularly polarized smart antenna that electronically reconfigure its beam by selecting among seven high-gain elements, each covering a different sector, is developed. 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 indoor settings, supporting more reliable and precise indoor positioning.

An another study [177], a single-port reconfigurable leaky-wave antenna with varactor-loaded cells generates orthogonal fan-beam modes for wide-angle DoA estimation is presented,as shown in Fig. 20. The corresponding DoA estimation error across the FoV in a single-source scenario is shown in Fig. 21(b) and 21(c) for complex-source reconstruction and amplitude-only source reconstruction, respectively . It covers −75° to 75° with low sidelobes using amplitude-only measurements. A data-driven voltage-pattern correction refines beam accuracy. Anechoic-chamber tests achieve sub-2° error over a 160° field of view. This offers a compact, single-port alternative to conventional multi-element arrays.

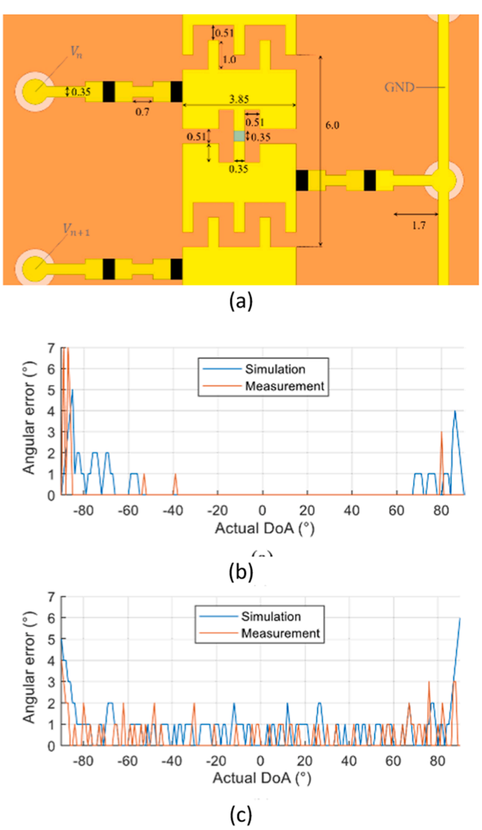

Fig. 20. Published reconfigurable antenna (a) Scheme of recofngiurable antenna b) complex source reconstruction and (c) amplitude-only source reconstruction [177].

A Wi-Fi indoor localization scheme equips a single AP with multiple low-cost switched-beam is introduced in [179]. Distinct beam modes produce uncorrelated RSS fingerprints, augmented by coarse DoA estimates from a MUSIC-based algorithm. Experiments in offices and corridors achieve sub-meter average error (≈0.87 m) from one AP. This design cuts infrastructure cost while maintaining high robustness in dynamic, multipath-rich indoor environments.

A compact single-input mmWave reconfigurable antenna with four switchable beams is for 62 GHz is designed in [180].The measurement of RMSE errors down to 0.44° at matched calibration angles, with cumulative errors under 8° when calibrated at 160°.This demonstrates that even limited-scan mmWave reconfigurable antennas can deliver practical beamforming and sub-degree to few-degree DoA accuracy without phased-array complexity. In [178], an electronically controlled beam-scanning leaky-wave antenna is used to create virtual subarrays for coherent-signal DoA estimation. Ten-element LWA hardware and electronically switched beam angles simulate multi-channel reception in a compact form factor. Fig. 21(a) shows the schematic of the proposed simulated LWA, while Fig. 21(b) presents the RMSE as a function of SNR. Simulations show accurate recovery of two equal-power coherent sources at various SNRs, with resolution down to 6°, and robustness to low SNR.

In another study, an analog DoA system is developed in [181]used a fixed-frequency, electronically scanned CRLH LWA with reverse-biased varactors and two power detectors to scan the beam and estimate arrival angles from the differential received power at the antenna's two ports. This method supports forward, backward, and full-space operation, achieving full-space DoA with only half-space scanning, and was validated by full-wave simulations and measurements at 2.445 GHz showing accurate angle peaks after simple gain equalization. The approach minimizes hardware by eliminating multi-element arrays, phase shifters, and A/D chains. Another reconfigurable example is a half-cube IEEE 802.15.4 node developed in [182], which integrated a dual-face, circularly polarized switched-beam antenna. Each face is driven by a 2-bit passive beamforming network, producing four uncorrelated beams, for a total of eight beams spanning 180°. The system estimated the azimuthal DoA with a mean error of 2.26°, with 90% of estimates within 5.22°, all achieved without active phase shifters, large arrays, or high-resolution ADCs.

A two-dimensional DoA estimation system presented in [183] employs a uniform circular array of radiation-pattern-reconfigurable antennas, each electronically switchable among multiple directive patterns to synthesize virtual array for azimuth and elevation estimation. Anechoic chamber experiments demonstrate high angular resolution and robustness against mutual coupling, with errors confined to a few degrees across the full field of view. This approach offers a compact and cost-effective alternative to conventional multi-channel arrays for full-space DoA estimation in wireless sensing and localization.

A machine-learning-based RFID localization system is presented in [15] employs a four-element, pattern-reconfigurable UHF RFID reader antenna array, in which an SP4T switch sequentially activates each high-gain, circularly polarized patch to collect RSS fingerprints from passive tags across different azimuth sectors. Experimental results show that 90% of tags were localized within 1 m and 67% within 50 cm, without the need for multiple fixed readers or phase-based ranging. In [58], a low-cost ESPAR-antenna- is proposed that integrates a 12-element parasitic array with SPDT-switch-controlled load states to

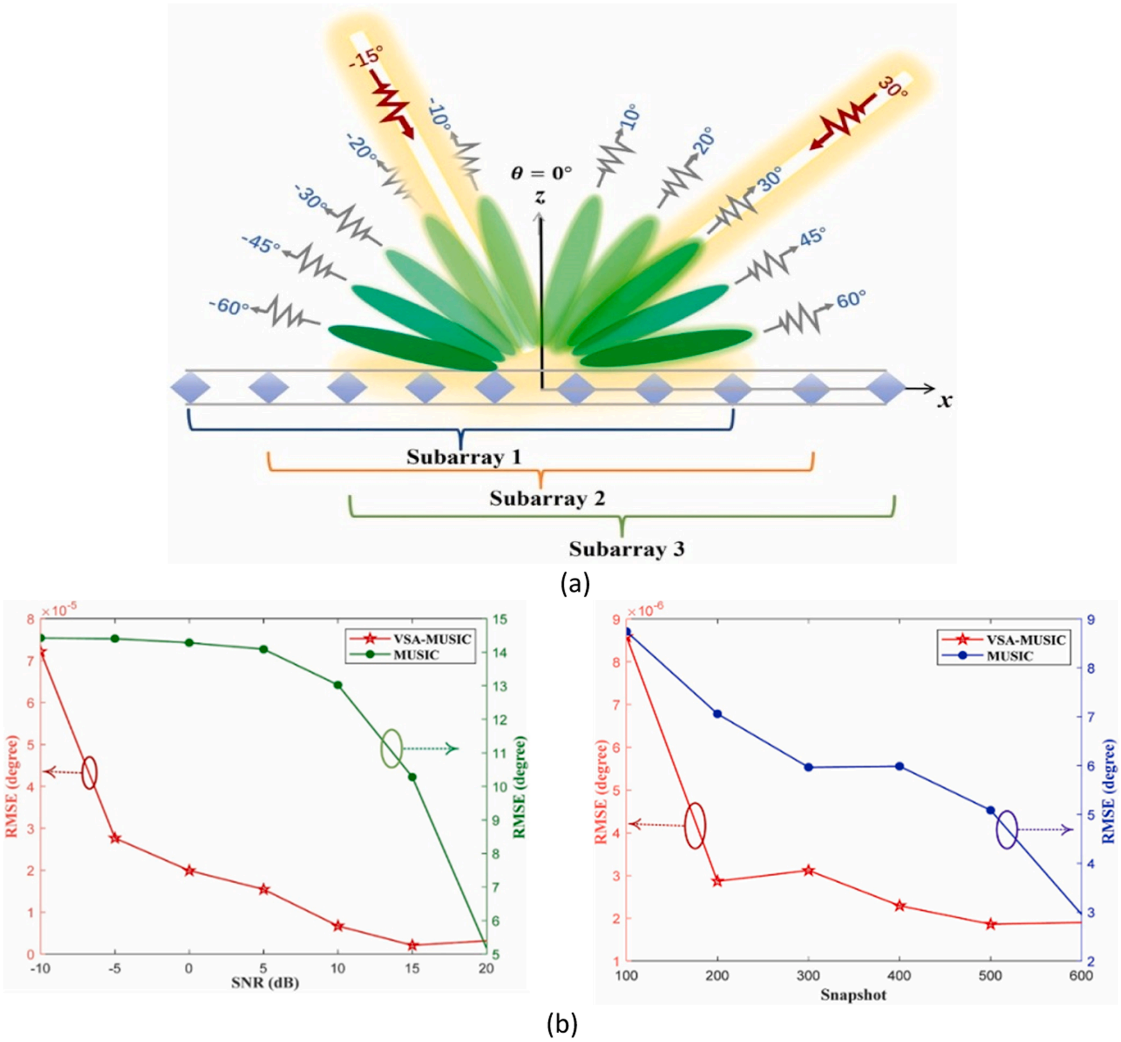

Fig. 21. (a) Schematic diagram of the LWA simulation(b) . Comparison of RMSE versus SNR [178].

generate 12 discrete directional patterns, enabling both beam steering and DoA estimation through an embedded implementation of the power-pattern cross-correlation algorithm using only RSS measurements. The experiments at 3 m, 5 m, and 10 m demonstrated RMSE DoA errors of 7.91°, 6.58°, and 9.47°, respectively.

A 2.45 GHz narrow-beam indoor positioning antenna system presented in [93] integrates a 4 × 4 phase shifter with a four-element printed dipole-Yagi array, selected via an SP4T switch to steer the main lobe to −36°, −12°, +12°, or +37°. Each fan beam provides an elevation beamwidth of ∼90°, combining high gain (9.1–9.8 dBi) with reduced multipath sensitivity. In a 10 m × 12 m × 5 m test space, mean localization errors were 0.70 m, with the best error-to-area ratio (0.023). These results demonstrate that the narrow-beam BSAA significantly improves IPS accuracy compared with omni-antenna baselines. Another notable study [120] presented a single-anchor indoor localization system that combines a 12-element ESPAR antenna with RSSI fingerprinting, exploiting both its 360° scanned directional main beam and its narrow minimum-radiation patterns. Using simple SPST switching of the parasitic elements, the method estimates position through nearest-neighbour matching, achieving mean errors of 1.61–1.86 m. These results show that ESPAR pattern diversity can significantly enhance single-anchor RSSI fingerprinting accuracy without requiring multiple anchors, complex phase processing, or heavy infrastructure.

A combined DoA–ToA localization system is developed in [65]using a single anchor with a 4–7 GHz sequential-rotation antenna (SRA). An SP8T switch sequentially activates eight circularly polarized patches, transmitting wideband pulses for ToA measurement and recording peak RSS for DoA estimation. Phaseless DoA estimators (phaseless MUSIC) achieve mean errors below 3°, while range accuracy reaches sub-20 cm—all using scalar RSS and a low-complexity switching mechanism, without multiple anchors or coherent phase measurement.

Overall, reconfigurable antennas offer flexible, low-cost solutions for wide-area coverage and adaptive indoor localization, demonstrating sub-meter to sub-degree accuracy without the complexity of large, phased arrays. However, most existing designs still face practical limitations such as dependence on precise calibration, switching and control network losses, and performance degradation in dense multipath conditions, underscoring the need for more scalable and resilient architectures for real-world indoor deployments.

5.6. Metasurface antennas

Metasurfaces, engineered 2D structures with subwavelength unit cells, have opened unprecedented possibilities for manipulating electromagnetic waves, leading to a new generation of antennas with unique properties [134–178,180–185]. Recent advancements include metasurface-based antennas that offer very high gain, steerable beams, and specific polarization control, often in a low-profile form factor. For indoor positioning, metasurface antennas can be designed to create highly focused beams for precise AoA estimation or to generate specific radiation patterns that enhance coverage in complex indoor environments [186]. Their flat nature also makes them attractive for integration into walls or machinery surfaces. For instance, [25] proposed a single-port CRLH leaky-wave metamaterial antenna whose frequency-dependent radiation pattern enables angular localization of wideband sources. Using spectral dictionaries with correlation and equalization algorithms, the system retrieved angles with sub-degree accuracy, offering a low-cost alternative to phased arrays for beam-steering and indoor positioning.

Fig. 22 shows a dual-band quad-polarized antenna developed in [186] integrating a polarization conversion metasurface with a compact 4element dipole. Measurements confirmed wide RCS reduction bandwidths, gains up to ~10.95 dB, and axial ratios below 3 dB, marking the first integration of dual band PCM metasurface and quad polarized radiator for enhanced accuracy in multipath rich indoor positioning scenarios.

In [188] a compact single-port metamaterial antenna composed of finite periodic arrays of sub-wavelength ELC resonators, whose strong modal dispersion produces diverse radiation patterns across a narrow band is proposed. By matching measured spectral signatures to a reference dictionary through correlation and SVD-based equalization, the system localized narrowband emitters around 5.5 GHz with a precision up to 3°. This compact λ/3–2λ/3 planar antenna demonstrates a low-cost substitute for phased arrays in angular localization for mmWave and future 6G systems. Similarly, in [189] the authors introduced a compact single-port metamaterial antenna formed by finite periodic arrays of λ/6 resonators, whose strong modal coupling generates distinct radiation patterns across a narrow band. By exploiting these frequency–angular signatures and applying correlation-based matching, the system localized emitters around 5.5 GHz with angular errors as low as 2.7°. This approach demonstrates a lightweight alternative to phased arrays, enabling angular localization with reduced cost and hardware complexity for emerging wireless systems.

To improve impedance matching while enabling stable, wide-angle null steering antenna (NSA) for AoA estimation in compact, low-profile form factors, a high-impedance-surface-based null-steering antenna is presented in [190] integrates a two-element horizontal dipole array above a mushroom-type HIS reflector to equalize the element patterns. By exciting the elements with fixed amplitudes and varying their phase, the design scans a 60° H-plane null with > –30 dB depth from 2.4 to 2.6 GHz, without the complex amplitude control typical of conventional NSAs. A passive 2D DoA system is developed in [191] employs a fully metallic sectorial leaky-wave antenna with a corrugated metasurface bottom plate and concentric top-plate slots to leak the guided mode. The metasurface induces azimuth-dependent frequency–beam dispersion, varying the elevation scan rate with φ and embedding azimuth information in the frequency response. This single-port architecture estimates both azimuth and elevation without active beamforming. Measurements confirm that the anisotropic metasurface resolves the azimuth ambiguity of isotropic LWAs, providing a low-cost mmWave phased-array alternative.

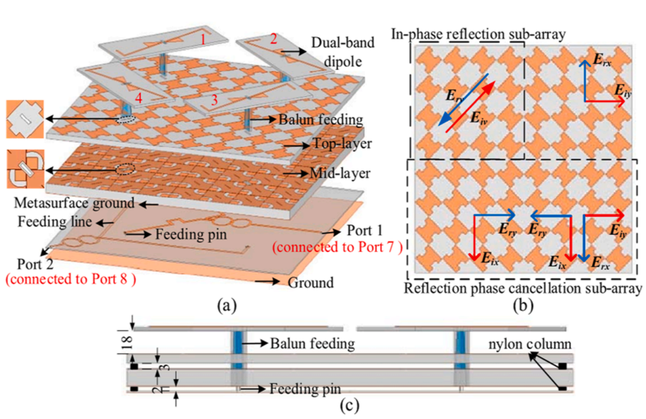

Fig. 22. Diagram of the published dual-band Antenna. (a) 3D schematic of the antenna. (b) Top view of PCM. (c) Side view of the antenna (Unit: mm)., [187].

A metamaterial-enhanced 4 × 4 microstrip monopulse array is designed in [192], as shown in Fig. 23, employing a CSRR-loaded metasurface superstrate to boost gain, widen bandwidth, and suppress sidelobes. Integrated with a waveguide monopulse comparator, it forms sum/difference beams without digital beamforming. Measurements show ~3 dB gain increase, bandwidth expansion from 5.6% to 8.2%, and >5 dB sidelobe reduction, providing a compact, high-accuracy solution for radar and communication tracking.

[193] A dual-band, dual-sense wearable textile antenna in [193]integrates a 3 × 3 AMC metasurface behind a truncated-corner, slit-loaded square patch to provide linear polarization at 2.45 GHz (WBAN/WLAN) and circular polarization at 1.575 GHz (GPS). The conductive AMC suppresses back radiation; boosts gain and lowers SAR. Measured gains are 1.94 dBi and 1.98 dBi with 27 % and 7.5 % bandwidths, delivering a compact, flexible, polarization-diverse metasurface-backed antenna for seamless indoor/outdoor localization. A fast leaky-wave antenna (FLWA) in [194] use a metamaterial waveguide combining a rectangular hollow waveguide with a periodic array of metallic rods to lower cutoff and enhance dispersion. Subwavelength rods guide a higher frequency–beam scan rate, with transverse slots for controlled. Measured results show −10 dB bandwidth from 7.15–7.85 GHz, beam scanning from 12°–72°, and ~12.5 dBi average gain, delivering a compact, stable-gain, high-scan-rate metamaterial FLWA for low-cost radar and positioning.

In [195], a dual-metasurface wideband antenna is presented that uses stacked complementary split-ring resonator (CSRR) layers above a microstrip patch to enhance bandwidth, gain, and pattern stability for positioning and communication. The CSRR layer acts as an AMC to suppress surface waves and improve front-to-back ratio. The design achieves 8.1 dBi peak gain with stable radiation, improving localization accuracy in multipath environments and providing a compact solution without complex feeds.

Metasurface-based antennas provide compact, low-cost, and highly versatile alternatives to phased arrays, offering beam steering, polarization control, and sub-degree localization accuracy in planar form factors well suited for integration into indoor environments. Nonetheless, their current reliance on narrowband modal dispersion, complex spectral dictionaries, and sensitivity to fabrication tolerances limits scalability and robustness, indicating that more broadband, calibration-resilient, and practically deployable metasurface architectures are needed for next-generation IoT and 6G positioning systems.

5.7. 3D (non-planar) antennas

Three-dimensional antenna designs leverage volumetric and curved geometries above the substrate plane, enabling superior control over radiation patterns, polarization, and spatial efficiency compared to planar structures. While these configurations can deliver enhanced gain and broader bandwidth, they inherently require greater physical volume and present increased fabrication and integration challenges. In RFID-based indoor localization, for example, such 3D antennas are attractive because they can provide higher gain and circular polarization, which reduces sensitivity to tag orientation. Recent studies have examined several three-dimensional helical antennas as candidates for RFID reader units [110,196] . For example, in [196] the authors propose a compact quarter-wavelength printed quadrifilar helical antenna for handheld UHF RFID readers in indoor inventory and asset tracking. The non-planar design employs four inverted-F quarter-wave resonators on a flexible substrate wrapped around a PVC cylinder, fed by a lumped-element quadrature network on a 60 × 60 mm^2 PCB to achieve circular polarisation and wide impedance bandwidth over 800–1000 MHz. Measurements show an axial ratio below 2 dB, peak gain of about

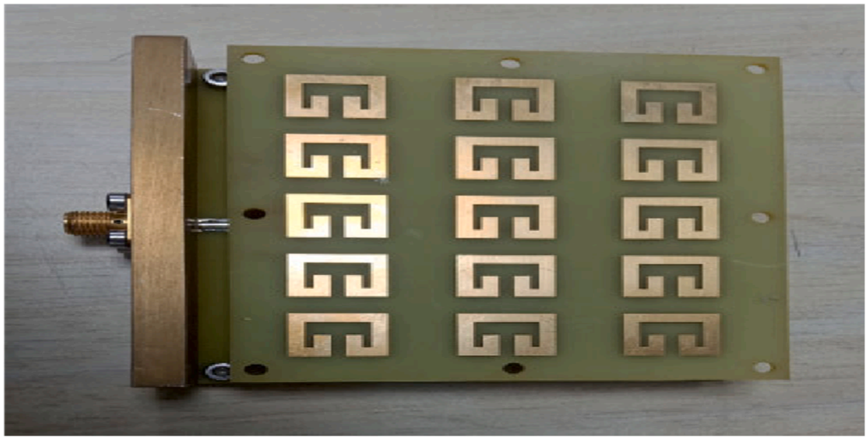

Fig. 23. Pentagonal microstrip antenna (PMSA) with loaded OLR [192].

3.2 dBi, and a LOS reading distance of roughly 7.2 m with a 4 W EIRP reader and a standard tag, yielding a small, low-cost CP radiator suitable for indoor RFID localization. However, the evaluation is restricted to LOS single-tag conditions and does not examine performance in dense multipath or multi-tag scenarios. More broadly, the physical size and mechanically complex construction of helical antennas make them difficult to integrate into compact handheld readers, limiting their practical deployment despite their attractive radiation characteristics.

Cavity-backed antennas are another attractive non-planar option for indoor positioning anchors, as they shield the radiator from the mounting platform and support array implementations with low mutual coupling, but this typically comes at the cost of narrow bandwidth or a relatively large footprint [197].For example, in [198]the authors design a non-planar quarter-mode air-filled SIW cavity-backed slot antenna array as a compact UWB anchor to achieve centimetre-level indoor positioning, as shown in Fig. 24. Using IEEE 802.15.4 UWB as the positioning technology and combining time-of-arrival-based distance estimation with phase-difference AoA (PDoA/MUSIC), the guard-trace cavity topology is optimised in the time and frequency domains to balance wide bandwidth, hemispherical radiation, high isolation from the

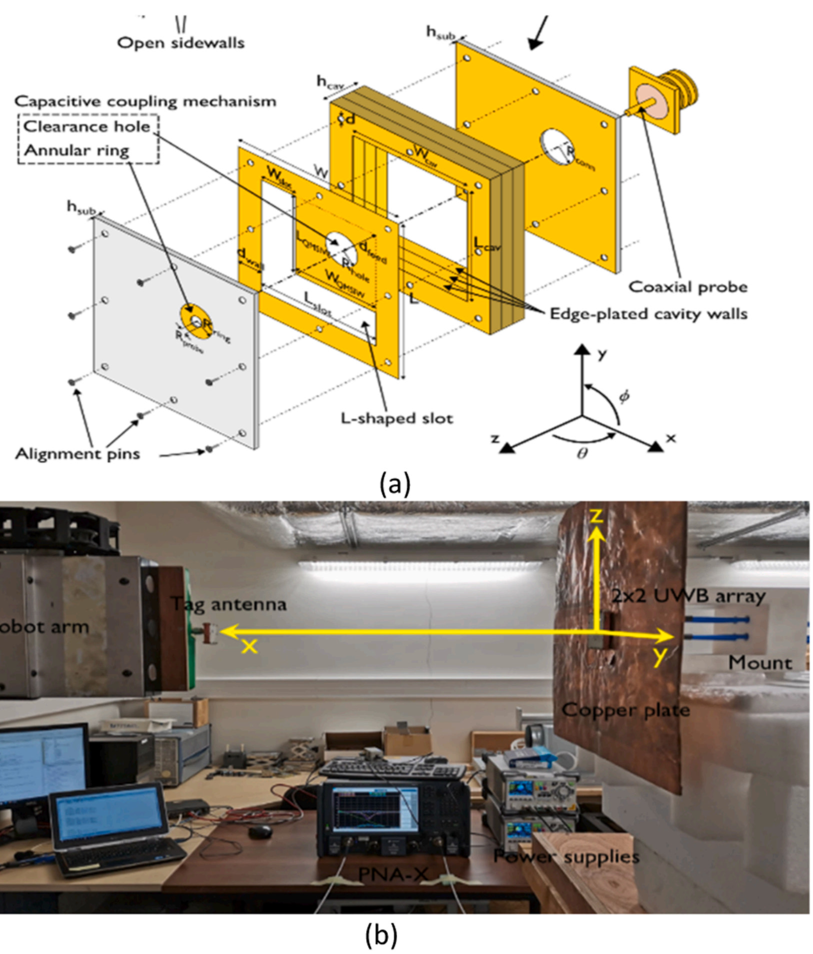

Fig. 24. The published antenna (a) overview of the topology and its design evolution (b) 2D AoA measurement setup [198].

platform, and low mutual coupling in λ/2-spaced arrays. Measurements on 2 × 2 and 1 × 4 arrays report all distance errors below about 2 cm and almost all angular errors below 5° in controlled tests, and <10 cm range error with 96% of AoA errors under 10° in a real canal trial. However, the study is restricted to UWB ToA/AoA in a single shipping scenario, which limits direct generalisation to other indoor positioning technologies.

The 3D-printed Dielectric Resonator Antenna (DRA) is a highly promising candidate for IPS owing to its manufacturing flexibility and ability to provide high gain, effectively compensating for the proximity impact of anchor nodes. For example, in [199] a compact non-planar 3D-printed dual DRA for UWB anchor nodes is designed to overcome the limited gain and weak angular selectivity of small planar UWB antennas in AoA/PDoA indoor localization. Using aperture-coupled stacked DRAs integrated on a small PCB for DWM3000 modules, the prototype covers 5.3–8.8 GHz with better than −10 dB matching, >20 dB isolation, broadside gains around 5–5.5 dBi, and 60–100° half-power beamwidths, providing directional coverage suitable for UWB indoor positioning anchors. The study shows that 3D DRA resonators can enhance angular selectivity and radiation efficiency of UWB anchors, but validation is limited to anechoic antenna measurements without full system-level localization tests. Another study [200] design a broadband rectangular DRA at 6.5 GHz with 20% fractional bandwidth to achieve uniform angular dependent delay for calibration-free TDoA-based indoor localization in service robotics as shown in Fig. 25. By suppressing higher-order modes and employing an elliptical ground plane to eliminate radiation pattern nulls, the antenna maintains consistent impulse response across the upper hemisphere, achieving position estimation errors of 1.24 mm in range and 0.26° in angle at 0.5 m distance, with accuracy improving at greater ranges. However, bandwidth remains inherently constrained by the single-mode operation requirement.

Horn antennas, while predominantly serving reference and calibration functions due to their substantial physical dimensions, have been employed in mmWave indoor positioning research. For example, in [201] highly directive horn antennas are used at both TX and RX—30° 3 dB beamwidth horns at 28 GHz and 8° 3 dB beamwidth horns at 140 GHz—to exploit multipath components for positioning, yielding mean localization errors of 5.72 cm at 28 GHz and 6.29 cm at 140 GHz. In [202], the authors employed rotational horn antennas at 2–4, 14–16, and 28–30 GHz to measure angle-of-arrival and delay-of-arrival characteristics in indoor LOS and obstructed-LOS scenarios. Results demonstrated that mmWave bands exhibit sparser specular-dominated multipath compared to richer diffuse scattering at lower frequencies, with consistent room electromagnetic decay rates (∼−0.25 dB/ns) across all bands.

Table 6 presents a comparative analysis of different antenna types and their applications in IPS, while Table 7 summarizes the corresponding performance trade-offs of these antenna solutions for IPS.

Table 6
Different antenna types for IPS.

Reference	Antenna Type	Frequency	Remarks	Antenna Gain
[95]	Tapered slot antenna	4.5–12.0 GHz	High gain and directivity for indoor obstacles.	8.92 dB
[44]	Patch antenna	2: 3.75–4.25 GHz	Higher gain, and 180° coverage, improving range by ∼100 m., Circular polarization	6.5 dB
[139]	Compact ultra-wideband	5: 6.24–6.74 GHz	Compact size, high efficiency, and low group delay variation for high-accuracy positioning	4.8 dB
[116]	Electronically Steerable Array Radiator Antenna	2.44 GHz	Steer beams in both elevation and azimuth, DoA estimation accuracy in complex environments	8 dB
[163]	Leaky-Wave Antennas	2.4 GHz (Wi-Fi band).	Offer a wide beam steering range (±60°), two-port operation reduces scanning time	5 dB
[99]	Probe-fed rectangle patch	4.4 to 7.8 GHz	Offers a wide bandwidth and compact size, low pulse distortion,	7.2 dB
[168]	Single leaky wave antenna (LWA)	2.4 GHz ISM band	Compact, planar design. Frequency-beam scanning. Simpler without active circuits.	14 dB
[138]	Aperture-coupled patch antennas	4 GHz and 6 GHz	Providing wide bandwidth, low dispersion, and low angular dependency	8.3dB

6. Discussion and future directions

The performance of any radio-based IPS is critically dependent on its ability to accurately measure signal parameters, which are then used to calculate a position. The antenna, as the interface to the physical world, is fundamental to this process. Each measurement technique—whether based on RSS, AoA, RTT, ToA or, TDoA—imposes distinct requirements on the antenna design to ensure accuracy and reliability.

Several core factors must be considered when designing antennas for IPS:

Operating Frequency and Bandwidth: The choice of frequency (e.g.,

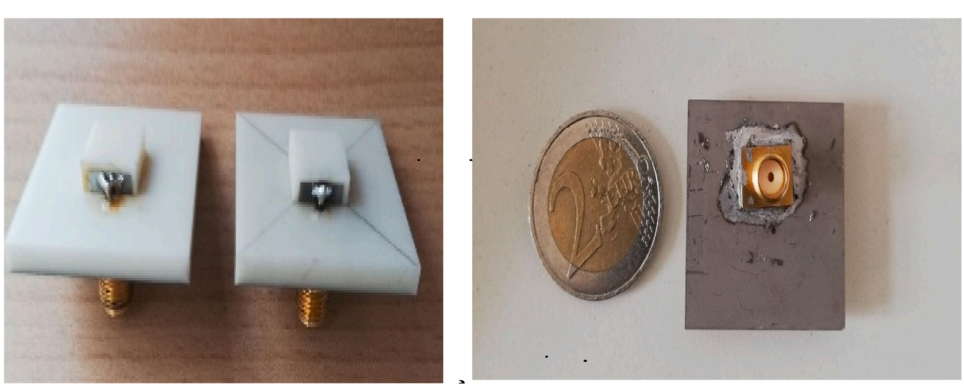

Fig. 25. The published fabricated DRAs. (a) perspective view (b) bottom view [200].

Table 7
Summary of trade-offs.

Antenna Type	Design Complexity	Accuracy	Cost	Applications
Patch	Low	Low–Med	Very low	IPS anchors/tags; BLE/Wi-Fi beacons; compact AoA arrays
Dipole	Very low	Low–Med	Very low	Basic anchors; array elements; multipath-assisted AoA
Leaky-Wave	Med–High	High	Moderate	Compact AoA anchors; beam-swept fingerprinting; mmWave IPS
Metasurface	Med–High	Med–High	Med–High	RIS/DMA-aided IPS; NLOS enhancement; smart surfaces
Reconfigurable	Medium	Med–High	Low–Med	Switched-beam AoA anchors; frequency-agile wearables
MIMO	High	Very high	High	High-precision AoA/AoD IPS; 3D tracking
Planar Array	Med–High	High	Med–High	Ceiling beamforming anchors; AoA grids

2.4 GHz, 5.8 GHz, UWB, or mmWave bands) dictates the trade-offs between range, signal penetration, and antenna size. The antenna's bandwidth must be sufficient for the chosen technology; for time-based systems like UWB, a wider bandwidth is essential as it enables higher-resolution timing measurements, which translates directly to superior positioning accuracy.

Radiation Pattern and Directivity: The antenna's radiation pattern defines its coverage. Omnidirectional antennas, which radiate uniformly in a plane, are ideal for mobile tags that must communicate from any orientation. In contrast, directional antennas focus energy, which is valuable for fixed anchor nodes to reduce multipath interference and for AoA systems that use antenna arrays to determine signal direction.

Polarization: In dynamic indoor environments where tags are in various orientations, circular polarization is often advantageous. It mitigates signal loss caused by polarization mismatch between transmitting and receiving antennas, leading to a more reliable link compared to linear polarization.

Miniaturization and Form Factor: For practical deployment, antennas on asset tags and personnel badges must be small, lightweight, and robust. Miniaturization is a significant design challenge, as it often involves a trade-off with antenna efficiency and bandwidth.

Efficiency and Gain: High radiation efficiency is crucial for maximizing range and ensuring a strong SNR. For time-based systems, high fidelity is also critical, meaning the antenna must radiate and receive pulses with minimal distortion to preserve the timing information essential for accurate distance calculation.

Indoor positioning systems may use a wide variety of antennas, including microstrip patches, MIMO arrays, leaky-wave antennas, reconfigurable antennas, and metamaterial-based designs. These antenna types of balance trade-offs among complexity, size, gain, bandwidth, and beam steering capabilities. Microstrip patch antennas provide compact, cost-effective solutions but are limited in bandwidth and gain. Ultra-wideband antennas deliver high temporal resolution yet require large, often bulky apertures. Passive frequency-steering reduces power consumption and cost but limits dynamic beam control. Switched-beam arrays offer spatial diversity and multi-beam functionality but increase physical size and may require complex switching networks. MIMO arrays enhance accuracy and robustness through multiple RF channels, at the expense of increased system complexity and power consumption. Choosing the appropriate antenna depends on application-specific priorities and constraints.

Antenna optimization for IPS remains a complex undertaking. The continuously changing spatial configuration of dynamic indoor environments where —characterized by moving objects and prevalent metallic infrastructure—creates demanding propagation conditions. Multipath propagation, NLOS conditions, and EMI persist as the primary design concerns that limit positioning accuracy and system scalability.

6.1. Future research directions and trends

Developing compact, high-performance antennas for indoor positioning systems holds significant potential. In complex indoor environments, advanced antenna designs—such as planar, MIMO, leaky-wave, reconfigurable, and metamaterial-based structures—can improve coverage, localization accuracy, and robustness against multipath and NLOS conditions. However, further research and optimization are needed to fully exploit their capabilities, ensure reliable performance under challenging propagation scenarios, and facilitate seamless integration into indoor infrastructures.

(a) Leveraging higher frequencies and mmWave antennas: The use of higher frequency bands, including mmWave, offers significant potential for indoor positioning. Antennas operating at these frequencies provide higher spatial resolution, increased localization accuracy, and wider bandwidth for time- and angle-based measurements. However, mmWave propagation is highly sensitive to blockage and multipath effects, requiring careful design of compact, high-gain, and beam-steerable antennas. Future research should focus on optimizing antenna arrays to ensure reliable coverage in complex indoor environments while maintaining efficiency and minimizing deployment complexity.

(b) Integration with reconfigurable intelligent surfaces (RIS): Reconfigurable intelligent surfaces present a novel approach to controlling radio propagation in indoor spaces. Antenna systems combined with RIS can dynamically manipulate reflection, scattering, and beam direction to mitigate NLOS conditions and multipath interference. Research should investigate antenna designs compatible with RIS-assisted channels, enabling adaptive coverage and improved positioning accuracy without a significant increase in the number of physical anchor nodes.

(c) Machine learning and artificial intelligence for antenna optimization and signal processing: Advanced computational methods can significantly enhance indoor positioning performance. Machine learning and AI techniques can optimize antenna array configurations, predict environmental effects on propagation, and refine signal processing algorithms for localization. These approaches also allow adaptive, real-time calibration of antenna systems, compensating for interference, environmental changes, and dynamic indoor layouts. The integration of AI-driven methods with advanced antenna designs promises improved robustness, reduced calibration effort, and higher overall system performance.

(d) Hybrid and Multi-Technology Systems: Combining different antenna types or integrating multiple positioning technologies can further improve system performance. For instance, hybrid deployments that utilize directional and omnidirectional antennas, or fuse signals from UWB, BLE, and Wi-Fi, can enhance coverage, redundancy, and accuracy. Research should explore how antenna design can support such multi-modal configurations without adding undue complexity or cost.

(e) Validation in real-world indoor environments: A critical challenge in antenna design for indoor IPS is validation under operational conditions. Future studies should include large-scale experimental deployments across diverse indoor layouts to evaluate coverage, robustness, and scalability. Close collaboration between researchers, system integrators, and industrial stakeholders is essential to ensure that antenna innovations translate into reliable, deployable positioning solutions.

7. Conclusion

This review has examined indoor positioning technologies and their reliance on antenna design for accurate operation in indoor environments. Wi-Fi, UWB, BLE, mmWave and RFID systems each offer distinct advantages, but their practical performance is strongly determined by the antennas' ability to support specific measurement techniques such as RSS, ToA, TDoA, RTT, and AoA. Bandwidth, radiation pattern stability, polarization, and beamsteering emerge as critical design parameters influencing both measurement fidelity and overall system reliability.

Indoor environments impose additional constraints, including multipath propagation, NLOS, and dense metallic infrastructure, which amplify the importance of robust antenna design. Advances in planar, MIMO, leaky-wave, reconfigurable, and metamaterial-based antennas demonstrate ongoing efforts to improve coverage, precision, and integration within indoor positioning systems.

Future research should prioritize antennas that maintain stable radiation characteristics under challenging conditions, enable beam steering or polarization agility, and combine compact form factors with high efficiency. Experimental validation in realistic indoor settings remains essential to ensure that antenna innovations translate into tangible improvements in positioning accuracy and system robustness. Furthermore, emerging technologies—most notably higher frequencies, Reconfigurable Intelligent Surfaces (RIS), and machine learning—present new opportunities for achieving higher precision, adaptability, and system intelligence in future IPS.

CRediT authorship contribution statement

Zayed Nasser: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tale Saeidi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Sahar Saleh:** Writing – review & editing, Supervision. **Nick Timmons:** Writing – review & editing, Supervision. **Saritha Unnikrishnan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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