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Review Article

A Review of Antennas for Indoor Positioning Systems

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This paper provides a review of antennas applied for indoor positioning or localization systems. The desired requirements of those antennas when integrated in anchor nodes (reference nodes) are discussed, according to different localization techniques and their performance. The described antennas will be subdivided into the following sections according to the nature of measurements: received signal strength (RSS), time of flight (ToF), and direction of arrival (DoA). This paper intends to provide a useful guide for antenna designers who are interested in developing suitable antennas for indoor localization systems.

1. Introduction

Indoor positioning systems have attracted research interest over the last decade. These systems can provide navigation, tracking, or monitoring services where Global Navigation Satellite Systems (GNSSs), such as Global Positioning System (GPS) [1], Global Orbiting Navigation Satellite System (GLONASS) [2], and Galileo [3] are infeasible solutions.

Indoor localization systems can be categorized as token or token-less according to whether or not the mobile unit carries or not any device used for the localization process [4]. Some examples of token-less systems are the Smart Floor [5], based on physical contact, more specifically stride characteristics recognition and the Easy Living [6] based on vision localization techniques.

Token localization presents a wider variety of technologies and systems that have been developed by different companies, research centers, and universities. These systems have been implemented based on several technologies: infrared (IR) [7, 8], Bluetooth [9–11], radio-frequency identification (RFID) [12, 13], wireless local area networks (WLAN) [14–20], Ultra-wideband (UWB) [21–26], ultra-sound [27–30], magnetic positioning [31], and audible sounds [32, 33].

Token indoor localization can be performed by three main techniques: triangulation (lateration and angulation), received signal strength (RSS) scene analysis (fingerprinting) and proximity based [34].

In indoor localization systems, devices have been categorized by its role in the system, although, according to different technologies, applications, or authors, several nomenclatures have been presented in the literature.

For a coherent reading of this paper, localization system devices are categorized into two groups: reference and mobile units. Reference units refer to the devices in known positions to the system, behaving as a reference and localization support for tracked units. Mobile units refer to the devices in unknown positions and desired to be estimated.

According to the technology, technique, and nature of the signals being processed, different antennas have been applied for radio frequency (RF) localization systems. The infrastructure of the localization system, formed by reference units, has been mainly integrated with omnidirectional radiation pattern antennas. Nevertheless, diversity of radiation pattern starts to become a desired feature for performance enhancement of these systems, which is possible due to sectorised antenna arrays (SAAs), multiple directive antennas with different discrimination zones, phased arrays, or even adaptive arrays, also called Smart Antennas [35].

The use of omnidirectional, directive, SAA, phased arrays and Smart Antennas can be applied to localization systems reference units based on different models of localization as presented in Figure 1. One common model is based on a set of omnidirectional antennas distributed over the localization scenario, as presented in Figure 1(a). This model is typically implemented for lateration and fingerprinting techniques, and it is widely implemented in Wireless Sensor Networks (WSNs). Another model passes by the use of directive antennas for a more confined localization based on proximity, widely implemented on RFID systems. This localization model is presented in Figure 1(b) as an access control system with directive antennas over the room doors. SAA/Phased/Smart Antennas can also be used for the localization process, which when well implemented, can provide higher coverage, higher accuracy, increased system capacity, signal-to-noise ratio improvement, multipath rejection, and the reduction of needed reference units leading to reduced system cost. However, these antennas inherently imply a larger and more complex implementation compared with previously described antennas. The localization process of systems integrated with these antennas can be performed based on: analysis of the signal received by the elements of one or more antenna arrays with appropriate signal processing algorithms support, or even performing a sweep of the radiation beam for the DoA estimation. SAA can be used to analyze the signal received by multiple directive elements or even by the sweep of fixed number of radiation beams, six in the case presented in Figure 1(c). Phased arrays or smart antennas can provide higher directivity and higher number of radiation beams making it suitable for single tracking and sweep of the radiation beam, as shown in Figure 1(d). Notice that Figures 1(c) and 1(d) are only presented with one single antenna array although several arrays can be applied. Despite of its benefits, the paradigm of localization based on these antennas demand proper modifications of the medium access control layer and routing techniques [36]. Besides the radiation pattern, antenna bandwidth and polarization are two important characteristics to consider when designing antennas for localization systems. Different localization techniques demand antennas with different bandwidth requirements and a proper polarization which can improve the quality of measurement signals. These antenna requirements will be discussed further in this paper.

Nowadays a wide variety of antennas have been applied for wireless communications although not all are suitable for localization systems. The aim of this paper is to review the state of the art of antennas for indoor localization systems and to describe their desired characteristics for system performance enhancement. Special attention has been given to reference unit antennas.

This paper intends to guide antenna designers to develop reference unit antennas suitable for indoor localization systems and is organized as follows. Section 2 describes the indoor localization techniques, followed by Section 3 that describes the antennas applied for indoor localization systems based on the type of measurements as RSS, ToA, and DoA. Section 4 finishes the paper with some conclusions based on the topics discussed.

2. Indoor Localization System Techniques

In this section, each of the main localization techniques applied for token systems are described. These techniques are divided as triangulation, RSS scene analysis, and proximity.

2.1. Triangulation. Triangulation is a technique that uses the geometric properties of triangles to estimate the target localization. It can be divided into two derivations: lateration and angulation.

Lateration or range measurement technique estimates the position of a mobile unit according to its distances from multiple reference units. The distance is mainly derived by computing the measured RSS, or derived by the signal propagation time of flight, ToF, typically divided as time of arrival (ToA), time difference of arrival (TDoA), and round-trip time of flight (RToF). The other derivation of this technique is the angulation, commonly called angle of arrival (AoA) or even direction of arrival (DoA). The subcategories of triangulation will be now described.

2.1.1. Time of Arrival (ToA). ToA technique derives the distance between two devices by measuring the one-way propagation time between them, knowing a priori the signal propagation speed. The distance between the device d is given by $d = s(t_2 - t_1)$, where t_1 is the signal sent time, t_2 the time of the signal arriving at the receiver, and s is the signal propagation speed. The calculated relative distance between the devices together with the knowledge of the reference units absolute positioning provides the chance to calculate the localization of mobile units.

The estimation of the localization can ideally be seen as the interception point of circumferences (or spheres on 3D plane) centered on reference units and radius (R_x) of estimated distance to the mobile unit as shown in Figure 2.

Nevertheless, in real scenarios where multipath fading and shadowing are present, an area of uncertainty is found instead of one exact localization point. To minimize these errors, several algorithms have been presented in the literature [37].

For the correct position estimation based on ToA techniques, a precise synchronization of all networks devices (mobile and reference units) is required, also as the timestamp information (sent on the transmitted packet). ToA techniques provide high accuracy although at a cost of higher hardware complexity.

2.1.2. Time Difference of Arrival (TDoA). TDoA technique determines the relative position of the units based on the following two different approaches.

(i) Difference in the propagation time of a transmitted signal between a single unit and three or more reference units.

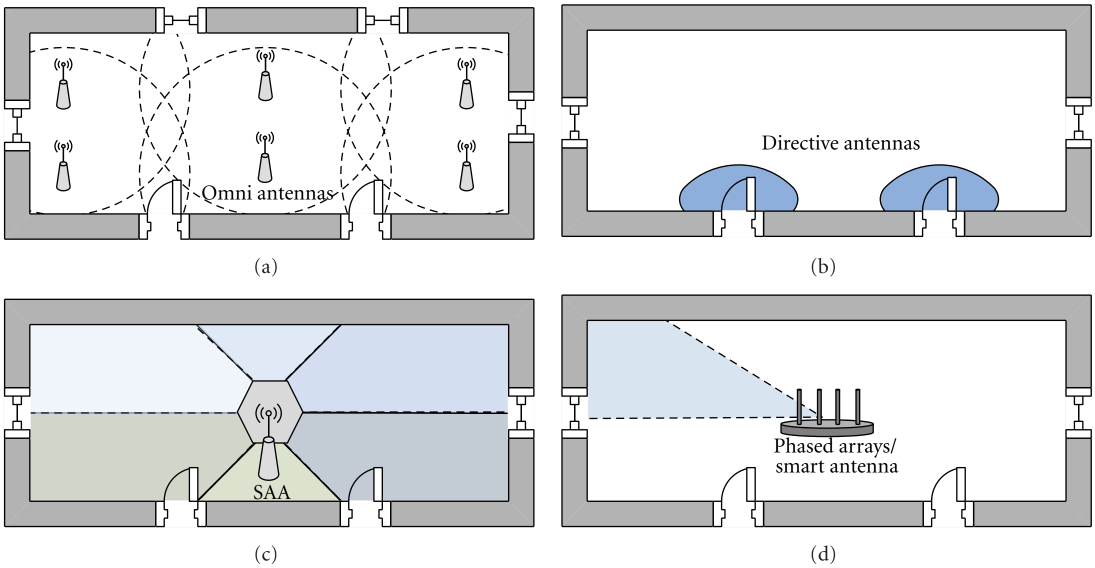


Figure 1: Localization systems models: (a) based on omnidirectional antennas; (b) based on singular pattern directive antenna; (c) integrated with SAA; (d) integrated with phased or smart Antennas.

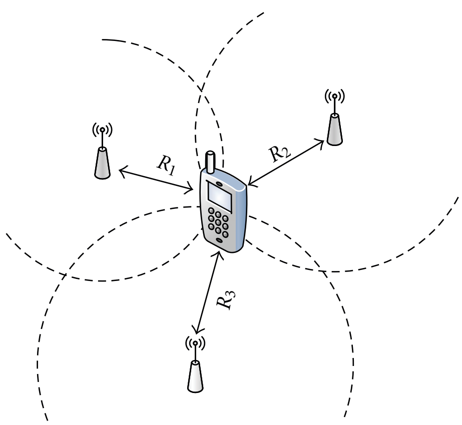


Figure 2: Representation of ToA localization technique.

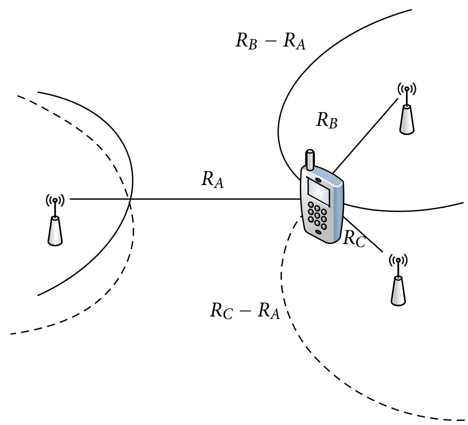


Figure 3: TDoA localization technique representation.

(ii) Difference in the propagation time of multiple signals from a single source unit and three or more reference units.

The first described approach requires precise synchronization of reference units. TDoA can be estimated after performing the correlation between received signals for each pair of measuring units. The TDoA refers to the time value which maximizes the cross-correlation function. By this reason only reference units (rather than all units for ToA methods) need to be synchronized. The distance estimated to the mobile unit by the TDoA between two reference units is given by a hyperboloid function [17]. Based on the chosen TDoA pairs, the interception of two hyperboloids gives the position of the mobile unit, as shown in Figure 3. These relative coordinates, along with the knowledge of reference units' position, provide a base to estimate the localization of mobile units.

In the second case, the mobile units need to be equipped with extra hardware capable of sending two types of signals simultaneously. These signals must have different propagation speeds, like radio/ultrasound [27] or radio/acoustic [33]. Knowing at priori the position of three reference units and the TDoA between the two signals, the localization of the mobile units can be estimated. This approach does not require synchronization of the infrastructure, although they need extra hardware to send the second signal, which typically has a limited range. TDoA localization systems also provide high accuracy.

2.1.3. Round Trip Time of Flight (RToF). RToF technique, or ToA two-ways ranging, measures the complete trip ToF of the signal between the transmitter and the receiver units. These systems are identical to radar systems, although the receiver unit performs some signal processing instead of simple signal reflection.

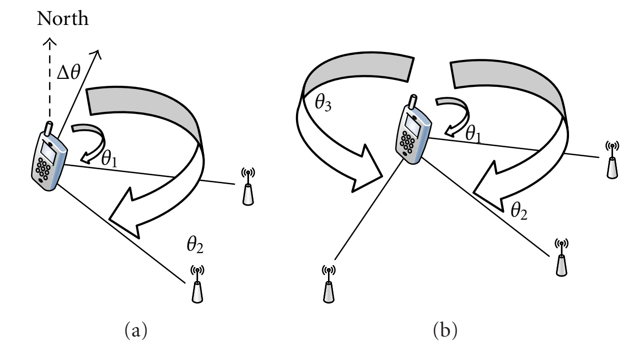


Figure 4: AoA technique representation: (a) AoA with mobile unit known orientation. (b) AoA without mobile unit known orientation.

These systems do not demand precise clock synchronization as systems based on ToA; nevertheless it is crucial to know the exact processing time of the "responder," typically measured in a calibration phase. Errors on this measurement have significant impact for the system localization resolution, critical for small range systems. The representation of this technique is presented in Figure 2 although the measured RToF represents the propagation time of the signal to cross distance R_x twice with the incremental time processing delay.

When integrated with proper synchronization capabilities, this technique can even be applied for passive RFID technology, where the reference units (readers) will be able to energize the "responders," passive RFID tags and measure the RToF.

2.1.4. Received Signal Strength Indication (RSSI). RSSI represents the receiver measured RSS and can be used to estimate the distance between devices based on signal attenuation models, typically log-normal [38]. This technique has the advantage of simplicity of implementation and low cost mainly because wireless system receivers are commonly integrated with RSS measurement capabilities, which were initially used for other purposes such as automatic gain control or even transmit power control.

In real environments such as indoor environments where it is difficult to find the LoS (Line of Sight) between units, the RSSI is highly affected by multipath fading, shadowing, and even antenna type, making it challenging to develop a mathematical model of the channel that matches with the real propagation, resulting in inaccurate distance estimations. Other parameters such as Link Quality Indicator (LQI), Packet Reception Ratio (PRR), Signal-to-Noise Ratio (SNR), and Response Rate (RR) can be used to support the localization process. When low cost is in priority over accuracy, these systems provide a suitable solution. Converting the RSSI into distance, the estimation of mobile unit localization can be performed by the interception of three circumferences centered on the reference units, as presented in Figure 2.

2.1.5. Angle of Arrival (AoA). Angulation is another derivation of the triangulation technique, commonly called angle of arrival (AoA) or even direction of arrival (DoA). It estimates the unit localization computing angles relative to multiple reference points. This angle can be related to its own unit, to an electronic compass or even to a second signal received by the unit. The estimation of the AoA is done by the use of several directive or antenna arrays as presented in Figures 1(c) and 1(d) and described in Figure 4.

The main advantage of this technique is that if the mobile unit orientation is known, only two measurements of noncollinear reference nodes are needed for 2D localization (three for 3D localization), and there is no need for time synchronization between units, as presented in Figure 4 [39]. The disadvantages of this technique rely on the need or large and complex hardware requirements.

The localization based on these systems relies on accurate angle measurements which become less precise as the unit moves further away from the measuring unit and are highly affected by multipath or even by directivity of the measuring aperture.

2.2. RSS Scene Analysis. RSS scene analysis is a localization technique that estimates the mobile unit position matching the online scene collected features (fingerprints) with the closest fingerprints saved a priori on a database, as presented in Figure 5.

This technique is performed in two phases: offline and online. During the offline phase, the position coordinates and respective RSS collection from nearby reference units is gathered. During the online phase, localization fingerprinting algorithms uses the observed RSS collection to estimate the mobile units' position.

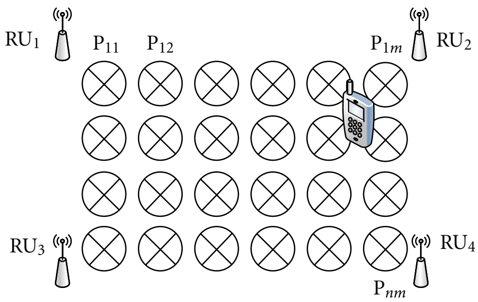
Positioning with signal strength fingerprinting algorithms is usually based on deterministic and probabilistic approaches, neural networks, and decision trees. A comparative survey of Wireless Local Access Networks (WLAN) location fingerprinting can be found in [40].

The main drawbacks of this technique are the consuming time calibration, which needs to be updated in case of localization environment changes, and the need of high computational cost and space to store network information.

2.3. Proximity. The proximity method simply provides symbolic relative localization information. If a mobile unit is detected by a single reference unit, the mobile position is associated to it. In case of more reference units' detection, the mobile unit position is related to the unit that detects the strongest signal. This technique is commonly applied to localization systems based on infrared, RFID, or even cell identification, where positioning is related to the cellular network cell that the device is using at a given time.

3. Antennas for Indoor Localization

Indoor localization systems have been widely implemented with a large variety of antennas. In this section, an overview of localization system antennas will be presented focusing on antennas that are integrated on reference units. This section



Fingerprinting database

	P_{11}	P_{12}	…	P_{nm}
RU_1	RSSI	RSSI	RSSI	RSSI
RU_2	RSSI	RSSI	RSSI	RSSI
RU_3	RSSI	RSSI	RSSI	RSSI
RU_4	RSSI	RSSI	RSSI	RSSI

Figure 5: RSS fingerprinting representation.

is divided according to the nature of the measurements for the localization process as: RSS; ToF, and DoA.

3.1. Antennas Applied for RSS Techniques. RSS localization systems can be divided based on RSS lateration, fingerprinting, and proximity techniques. The performance of these systems is inherently related to RSS measurements which in indoor environments are highly affected by several factors such as the following [41]:

(i) multipath fading and shadowing;

(ii) interference of other electrical field sources;

(iii) transceiver hardware inaccuracies on RSS measurements;

(iv) low probability of LoS path availability;

(v) user mobility.

Besides previously referred to factors, the used antennas have a significant impact on localization system performance that demands careful implementation according to several factors such as radiation pattern, polarization, gain, bandwidth, and efficiency.

As is standard for all antennas integrated with reference units, they are designed to be robust, inexpensive, impedance matched over the entire operational bandwidth, small, and highly efficient. These characteristics are important for the correct performance of the antenna which inherently affects the system localization errors. Nevertheless, other antenna characteristics such as radiation pattern and polarization should be carefully chosen according to different localization systems, as will be discussed next.

3.1.1. Antennas Applied for RSS Lateration. Antennas used as reference units for RSS lateration technique are desired with a perfect isotropic radiation pattern providing a homogeneous signal transmission over 3D dimensions. Unfortunately, these antennas do not exist. Due to this limitation, a simple and common solution passes by the implementation of antennas with toroidal radiation pattern, omnidirectional over the azimuthal plane, although with some directivity over the elevation pattern.

The mobile units, widely carried by human users for its localization, move and rotate according to the human motion profile, mainly over azimuthal plane with reduced rotation over elevation plane. Considering that this human movement and rotation profile is known a priori, the vertical polarized omnidirectional antennas on clear LoS are desired. To achieve these desired characteristics, antennas of mobile units should be applied on human heads providing a clear LoS or even on the shoulders, although this would provide impractical solutions for the user and specifically regarding human specific absorption rate (SAR). A possible solution to achieve these desired characteristics can be achieved by the use of wearable antennas [42, 43]. Considering a case where polarization orientation of the antenna on the user is guaranteed, copolar linear vertical polarized antennas on reference and mobile units are preferred.

Omnidirectional pattern with vertical polarization can be achieved with a correct design of a wide variety of antennas, although simplicity and cost make half-wavelength dipole or quarter-wavelength monopoles (in case of ground plane availability) the most used antenna types. For application with higher azimuthal range needs, omnidirectional with a higher gain and vertical polarization antennas can be implemented by the use of slot arrays or collinear arrays of half-wavelength dipoles can also be used [44].

In case of the mobile units that do not provide guaranteed polarization orientation, such as the use of localization devices as bracelets where the natural body movement causes change over time, reference units are desired with circular polarization (CP). The use of these antennas as reference units provides a solution less dependent on mobile unit orientation, although at the cost of localization range considering the typical linear polarized tracker antennas. A brief description of monopoles implementation on user is presented in Figure 6.

Several systems based on simple RSS lateration have been presented in the literature, mainly with commercial linear omnidirectional antennas [13, 14, 41, 45, 46].

3.1.2. Antennas Applied for RSS Fingerprinting. Localization systems based on RSS fingerprinting rely on an offline calibration phase which should be as similar as possible to the online phase conditions. These conditions refer not only to the localization scenario and environmental conditions, but also to the network units' characteristics during the calibration phase. Considering that calibration conditions are maintained, the system performance ideally does not depend on the antenna characteristics. However, the exact

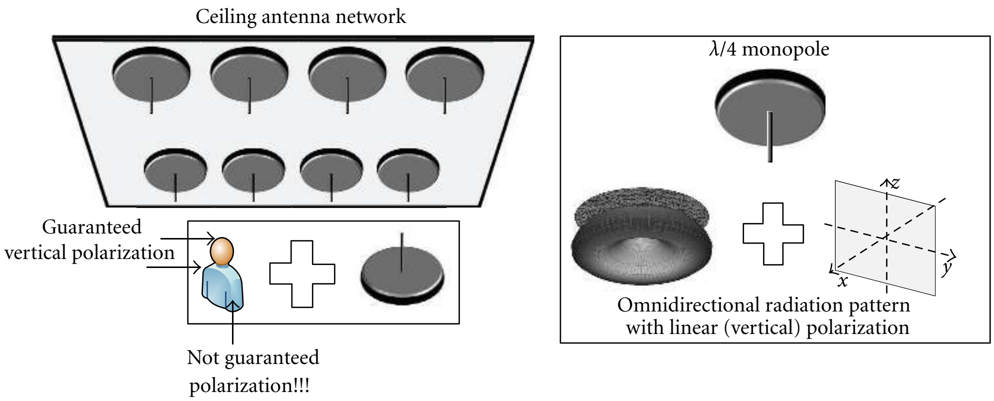


Figure 6: Monopole impact according to user integration position.

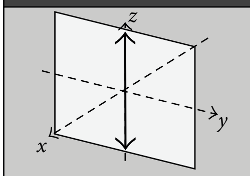
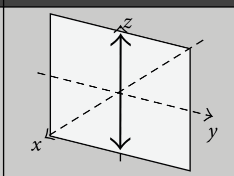
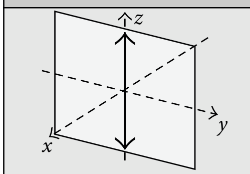
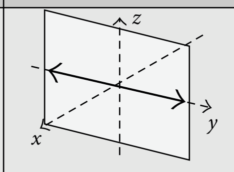
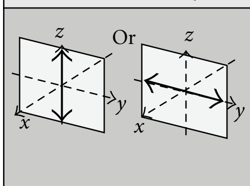
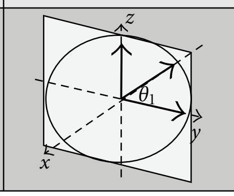
Transmitter polarization	Receiver polarization	PLF
		1
		0
		0.5

Figure 7: PLF according to different transmitter/receiver polarizations.

calibration conditions are not always guaranteed, but the less variance of the measurements when compared with the calibration results is of primordial importance. This variance in measurements can result from several interference sources or even by user movement and rotation.

Antennas with omnidirectional radiation pattern lead to smaller RSSI variances than directional antennas over the entire radiation pattern making its use preferable for fingerprinting. Another point of interest is its polarization orientation, depending on whether or not the polarization of antenna mobile units is guaranteed with vertical polarization, vertical polarized or circular polarized antennas should be preferred. The last approach provides less RSSI variance with the tracker rotation, leading to smaller errors based on fingerprinting techniques. The relation of polarization loss factor (PLF) with different system antennas combination is presented in Figure 7.

Localization systems based on fingerprinting have been widely applied for WLAN, WSN, and RFID, commonly integrated with commercial monopole and dipole antennas [12–18]. These characteristics are mainly justified once again by the omnidirectional radiation pattern, robustness, size, and cost. A wider quantity of fingerprinting-based localization systems have been presented in the literature, nevertheless, antenna characteristics during calibration and online phase is often omitted. For a correct analysis and validation of results this information should be mentioned regarding radiation pattern and polarization.

3.1.3. Antennas Applied for Proximity. Localization systems based on proximity cannot be considered real time localization systems (RTLS), in the sense that the mobile node localization is only performed if the mobile unit passes near reading zones and not constantly tracked over the localization scenario. Due to this different approach the antenna requirements also change in order to optimize the performance of these systems. This localization technique is mainly applied for Ultra High Frequency (UHF) and microwave passive RFID widely used in security/access control, asset management, transportation, and animal tracking.

These systems are generally implemented for localization of large quantities of RFID tags (RFID mobile units) under diverse localization scenarios where size, cost, efficiency, and reliability are the main restrictions. Being an antenna a tag main component, it is crucial to be inexpensive, with reduced dimensions and high efficiency [47]. The huge variety of RFID applications commonly without availability of ground plane makes dipole or dual dipoles for reduced orientation dependency, the most used tag antennas [48]. On these localization systems, due to cost and size, the located tag is typically a device with linear polarization and no uniformity of orientation. Impedance matching over operation bandwidth and mechanical robustness requirements are a key point. The antennas for the passive UHF RFID readers (RFID reference units) are mainly designed with high quality circular polarization to mitigate the problem of tags orientation sensitivity, high gain, and low side lobes for high directive range applications. Wide bandwidth is

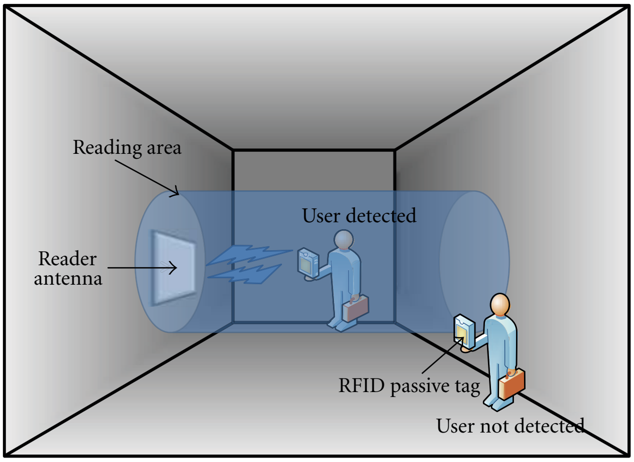


Figure 8: RFID System working with proximity technique.

also desired for universal UHF RFID compatibility (840–960 MHz). Although, if tags orientation is guaranteed, linear readers can be more suitable for creating a focused and oriented electromagnetic field used for greater range and deeper penetration. According to the localization scenario and desired application, omnidirectional radiation pattern antennas could be more suitable. A representation of a RFID system implemented with directive antenna is presented in Figure 8.

Several studies also have been performed on multiband RFID reader's antennas, although, antenna characteristics uniformity over the bands are harder to guarantee, which can affect the performance of the localization system.

Several reader antennas useful for RFID proximity systems have been implemented such as microstrip patch, dipole, slots, spiral, and helical antennas. A wide study has been presented for RFID reader antennas [49–56]. A comparison of handheld UHF RFID reader planar antennas and the reading range has been performed, [49], where fractal implementations were also analyzed. Unidirectional dual band antennas, with advantage of RFID operation over two bands, UHF and microwave RFID, also have been presented [50]. UHF RFID reader antenna with CP and high Tx/Rx isolation is discussed in [51] or even with different exciting techniques suitable for compact CP antennas [52]. Reader antennas covering the entire UHF RFID band (860–960 MHz) and a suitable CP have been reported, with helical, spiral shapes, and two corners truncated patches, respectively [53–55]. A discussion of the propagation aspects of passive RFID systems and suitable tag antennas has also been presented [56].

3.2. Antennas Applied for ToF Techniques. As previously mentioned, ToF system can rely on the measurements of DToA between two different speed propagation signals or even based on the ToA of ultrashort electromagnetic pulses. RF ToF localization systems can be efficiently implemented using UWB technology, mainly because of a high time resolution. UWB technology occupies a minimum bandwidth of 500 MHz or at least 20% of the centre frequency, demanding for a wide spectrum allocation for these applications (3.1–10.6 GHz) [57].

Indoor localization systems based on Impulse Radio (IR) UWB are commonly characterized by low power consumption and transmission of low data rate using very short-pulses spread over a wide bandwidth [58]. The high data spreading rate, due to low data over a large bandwidth not only allows the transmission over reasonable distances for indoor localization, but also improves the robustness to interference from narrowband interferers (jammers) and/or other UWB devices. Furthermore, a large absolute bandwidth allows very precise ranging, since the ranging accuracy is proportional to the bandwidth of the emitted signal [59].

UWB have been proved to be useful for indoor localization which made IEEE 802.15.4a Working Group regard UWB as the first choice for high accuracy indoor localization [60, 61].

The availability of synchronization in UWB systems combined with short transmitted pulses provides a chance to avoid multipath fading by reducing the overlap on the original signal. Nevertheless, there is always a chance of false alarms (identification of LoS as Non LoS (NLoS)) which degrade the localization accuracy [62].

Mainly due to the strong research over UWB transmission techniques over the last years, UWB, in general, is now considered better than conventional narrowband modulation and multiple access techniques at meeting the WSN requirements (low cost, low power consumption, robustness, localization accuracy) [63].

Once again, the antennas play a crucial role in the performance of these localization systems; however, the design of UWB antennas are much more challenging than narrowband antennas [64]. The main desired characteristics of the reference unit antennas for localization systems based on RF ToA can be described as follows:

(i) bandwidth coverage of the operational channel (minimum 500 MHz for 802.15.4a) and ideally covering the entire UWB band;

(ii) omnidirectional radiation pattern (for uniform coverage);

(iii) antenna uniformity over entire operational bandwidth (radiation pattern, gain, polarization, and impedance matching);

(iv) reduced dimensions and cost requirements (for integration with several equipments or printed circuit boards);

(v) high radiation efficiency due to the extreme low power transmitted signal, typically >70%;

(vi) linear phase in the time domain (constant group delay is desired to prevent pulse distortion);

(vii) physically compact with low profile (preferably planar due to easier manufacture and implementation).

Conventional UWB localization systems based on ToF (more than three reference units) are commonly used as unidirectional TDoA systems needing only precise synchronization of the infrastructure reference units [21–23]. Unidirectional ToA or bidirectional RToF techniques can also be applied. In ToA technique, the transmission time of the mobile unit need to be known, demanding synchronization of the entire network; for the RToF less demands of synchronization are required but an additional calibration phase should be performed [24, 65].

Several interesting UWB antenna approaches have been presented in the literature with different planar formats (e.g., rectangular, triangular, elliptical, spiral, fractal geometries) for high bandwidth, omnidirectional patterns and/or polarization concerns [66–68]; different feeding techniques (e.g., simple, two-branch, trident strip) that can improve polarization purity [69]; different geometries (step-shaped, cross-square, U-shaped, rolled, cross-plate) for stability of radiation pattern across the UWB band [70]; and integrated with suitable band-notches to reduce interference over specific bands [71–73].

Another desired characteristic for UWB reference unit antennas is its implementation with CP over the entire band, making it suitable to detect targets for which polarization is unknown [74]. A good example of UWB CP antenna is presented in [74], a spiral antenna with axial ratio below 3 dB from 3 to 14.5 GHz and return loss better than 10 dB from 3.75 to 18.6 GHz. This antenna also provides reduced pulse distortion and the feeding structure is performed by the integration of a tapered microstrip balun making its construction completely planar.

3.3. Antennas Applied for DoA. Localization based on DoA technique relies on accurate angle measurements, although, the accuracy of these systems is highly influenced by multipath reflections, shadowing, or even the directivity of the measuring aperture.

The estimation of the DoA can be achieved by the use of antenna arrays or directional antennas that improve the system in terms of capacity, connectivity, and spectrum efficiency. Different approaches have been proposed and applied to localization systems based on DoA, usually integrated with RSSI and ToF measurements.

Several different antenna implementations as reference units have been reported for positioning integrated with DoA approaches, some of them can be described as follows:

(i) narrowband SAA estimates the localization based on DoA algorithms considering RSSI and/or phase measurements of antenna elements [75];

(ii) UWB SAA estimates DoA based on amplitude difference of the received UWB pulse between each antenna elements [76, 77];

(iii) UWB mono-pulse radar systems estimates localization based on DoA (difference of signal phase and amplitude at receivers) and RToF to measure the distance [78, 79];

(iv) switch beam, phase antenna array or mechanical rotation of a directive antenna performing a sweep of the beam over the localization area (typically at a constant angular speed) to estimate DoA and the distance based on RSSI and/or phase measurements [80–84];

(v) UWB uniform linear array estimates localization based on DoA algorithms [85].

According to the previously mentioned approaches, one or several reference units are required and appropriate MAC protocols need to be developed in order to potentiate the correct localization environment coverage and localization resolution [36].

Antennas suitable for localization based on DoA are required with different requirements according to previous approaches for DoA estimation. For narrowband systems, reference units are typically desired with narrow beam width to provide higher accuracy and higher range, CP to mitigate polarization diversity problems and reduced coupling between neighbor antennas to avoid radiation pattern distortions; for DoA based on UWB systems, the requirements are similar to UWB ToF systems with the addition of shorter beam width and reduced coupling between the neighbor antennas. Both approaches are desired to be applied as printed circuit boards providing manufacture and implementation cost advantages.

Antennas suitable for DoA with possibility of independent localization zones have been presented. SAA over a semidodecahedron shape with CP and designed for ISM 2.4 GHz systems are presented in [75, 86], although [86] presents higher gain by the use of patch excited horn antenna array.

In [76, 77, 87], SAA for UWB applications are presented. Antennas implemented for azimuthal coverage by the use of six directive antennas into prismatic structures are presented in [76, 77, 87] with seven multilayer microstrip antennas integrated into a semispherical polyhedral antenna array configuration. DoA also can be obtained by other switch beam UWB antennas such as double square loop antennas [88] and linear arrays implemented with beam forming networks [89]. UWB radar systems based on DoA and RToF have been presented in [78, 79]. Similar implementations have been presented for narrowband WSN based on sectorial sweeper or tracking systems. The distance of these systems is not based on RToF but on RSSI measurements. In [80, 82] the systems are based on linear antenna arrays and in [83] on a rotating directive antenna.

Circular monopole antennas have also been applied to DoA finding based on sector switching, obtained by the following two main topologies [90, 91].

(i) One central monopole operating as main antenna for emitter/receiver connection while surrounding peripheral circular array may be switched connected as different reactive loads, usually called electronically steerable parasitic array radiator (ESPAR).

(ii) No central monopole is present and the circular symmetry is broken by connecting specific antenna elements to the emitter/receiver, where the others are connected to some reactance or short-circuited to the ground plane.

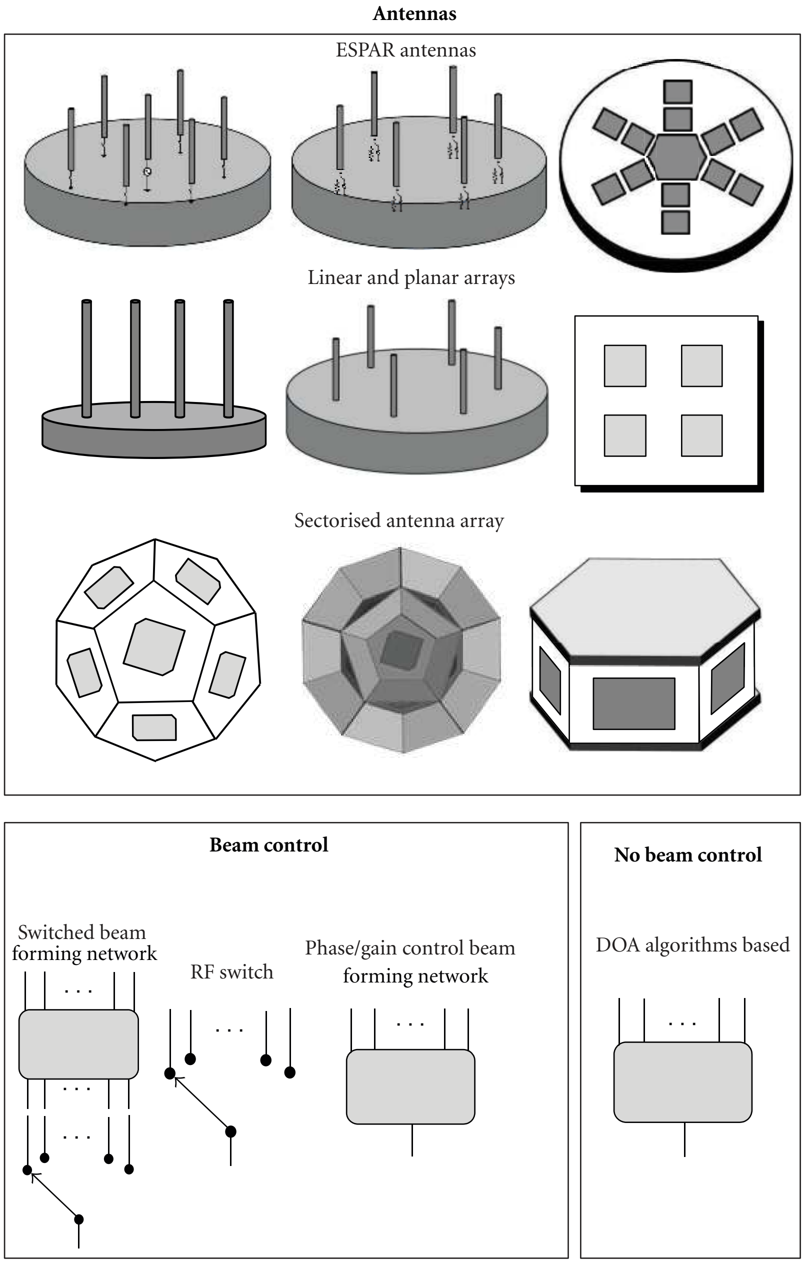


Figure 9: Antennas and beam control networks for DoA.

Several ESPAR antennas based on monopoles have been presented, mainly for 2.4 GHz ISM band with different number of parasitic elements [92–95] or even for UWB [96].

This previous topology of switch beam based on parasitic elements also has been reported with other antenna types such as slot and planar microstrip antennas [97–102].

For a more clear description of the antennas implemented for DoA, we divided the antenna arrays into three main blocks, ESPAR antennas, Linear/Planar Arrays, and SAA. Each of the previous antenna arrays can be connected to different beam control networks according to the DoA estimation approach, as presented in Figure 9.

The first antennas block provides the beam control by the integration and control of the reactance of parasitic elements, being here defined as ESPAR antennas. Different antenna types can be used as radiating and parasitic elements such as monopoles, microstrip, or even slot antennas. Each of these approaches can even be integrated with or without a central radiating element.

The second antenna block is described as linear and planar arrays, where the gain/phase control of each element provides the chance to manipulate the array radiating beam. These arrays can be performed with different antenna types and format, linear or circular arrays, or even diverse planar forms.

The last antennas group described in this paper for DoA calculation is referred as Sectorised Antenna Array (SAA) and represent the antenna group based on a set of directive antennas in different directions. These solutions are typically designed with prismatic implementations providing azimuthal coverage or with polyhedral implementation for a semispherical coverage. These antennas can be implemented with any directive antenna elements, although they are typically implemented with planar formats due to size and cost constrains.

According to the implemented DoA localization approach, previous referred antennas can require a radiation beam control which can be performed by several possible techniques, such as: switched beam forming networks (e.g., Butler and Blass Matrix), switch control of radiating antenna elements or even by a phase/gain control for each antenna element. Although, localization based on DoA can also be performed without beam control, using the antenna arrays received signals and appropriate signal processing algorithms (e.g., MUSIC, ESPRIT [103–105]).

Mechanical rotation of a directive antenna can also be performed to control the radiation beam, and like this, be used for DoA estimation. Although, in Figure 9, this approach is not presented, being only considered the description of static antenna solutions.

4. Discussion

In this paper, the main types and requirements of reference unit antennas for indoor localization systems are presented based on three different measurements: RSSI, ToF, and DoA. The first approach typically relies on narrowband omnidirectional with linear or circular polarized antennas according to polarization orientation on mobile units. ToF approaches are mainly designed with similar needs, although with larger bandwidth requirements which lead to new design constrains such as uniformity of antenna characteristics over the entire operational bandwidth and linear phase in the time domain.

DoA provided a much complex and wider arrangement of antennas that can be used as an arrangement of sectorised antennas elements or by a rotative or switch beam over the space. Several antenna approaches for localization such as linear and planar antenna arrays, SAA, ESPAR antennas have been presented.

Based on the signal nature for the localization estimation, different reference unit antennas can be more suitable than others, as previously explained. For demonstration purposes consider a localization system based on fingerprinting. The choice of several omnidirectional antennas with CP would be preferred over a single or few SAA considering the same number of antenna elements. Due to the reduced distribution of SAA elements over the localization system, they also would become more susceptive to variations on localization system environment. However, if we consider a conference amphitheater, typically with a high ceiling, providing a good probability of LoS with the mobile units, the use of a central or few SAA would be preferable reducing mounting efforts of the localization system to fewer devices, with expected similar results.

Noncontinuous low power localization systems could also benefit from high efficient SAA/Smart antennas compared with omnidirectional antennas, being more suitable for energy harvesting capabilities during the nonlocalization intervals [106].

Localization system performance can highly benefit from the use of appropriate reference unit antennas according to the localization technique. The antennas have a direct impact on system accuracy and on availability, number of reference units, portability, size, cost, and power consumption.

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