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APPLIED RESEARCH

Antenna Characteristics Contributions to the Improvement of UWB Real-Time Locating Systems' Reading Range and Multipath Mitigation

AMINA BENOUAKTA, (Student Member, IEEE), FABIEN FERRERO, (Member, IEEE), LEONARDO LIZZI, (Senior Member, IEEE), AND ROBERT STARAJ, (Member, IEEE)

CNRS, Laboratory of Electronics, Antennas and Telecommunications (LEAT), University Côte d'Azur, 06000 Nice, France

Corresponding author: Amina Benouakta (amina.benouakta@univ-cotedazur.fr)

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ABSTRACT Indoor object localization and positioning is part of the space-awareness concept which has seen a rising popularity in recent Internet of Things (IoT) research and applications. This article presents a novel method to improve the localization performance of ultra-wide band (UWB) real-time locating systems (RTLS) by improving the transmitting and receiving reader and tag antennas. Patch directional UWB antennas with relatively higher gain compared to the generally used standard omnidirectional monopole UWB antennas have been exploited to achieve a larger localization range. Furthermore, the patch antennas were designed to have wideband circular polarization to achieve two objectives: a received power independent of the orientation of the tagged objects that need to be detected, and the filtering of unwanted multipath signals. A measurement campaign was conducted using a commercially available RTLS with conventional antennas and then with the newly designed antennas. A comparison between the localization results of the two antenna types demonstrates an improved range with almost 100 m difference, received power independent of tag orientation, and increased multipath mitigation with the directional circularly polarized antennas.

INDEX TERMS Antennas, circular polarization, indoor localization, ranging, multipath, real-time locating systems (RTLS), ultrawide bandwidth (UWB).

I. INTRODUCTION

The future of real-time locating systems (RTLS) announces itself to be a prominent topic as its applications find a niche in most domains such as industrial, scientific, economic, and social [1], [2].

RTLS technology for high-accuracy localization is based on the impulse-radio ultrawide bandwidth (IR-UWB) standard and was first introduced with the aim of locating objects in indoor environments [3], [4] such as inside buildings, mines [5], and anywhere Global Positioning System (GPS) tends to fail owing to harsh propagating conditions. For example, this is the case when the presence of obstacles and reflecting objects leads to multipath components that affect the recognition of the desired signal. Fortunately, the UWB standard is more robust against such propagation hinders thanks to its wide spectrum (3.1 GHz - 10.6 GHz), where one UWB channel has a bandwidth of 0.5 or 1 GHz [6], [7], [8].

Current industrial real-time locating architectures target the most accurate indoor localization of objects [9]. Such architectures are primarily composed of one or several readers and tags. While attempting to locate a tagged object, they receive continuously, real-time ranging signals in both the uplink (target -reader) and downlink (reader -target), or only in the uplink, depending on the ranging method used (two-way ranging (TWR) or time difference of arrival (TDoA), respectively [10]). Although the highest accuracy is targeted during this continuous exchange, as long as the locating system operates in a real imperfect environment, the system will most likely fail to locate the object precisely at least once among its total ranging attempts, especially in the case of changing environment due to the mobility of the

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tagged object. For this reason, the goodness of an RTLS is not only defined by its accuracy, but also by how consistently this accuracy is achieved. In some applications, such as localization using radio frequency-identification (RFID) technology, meter level accuracy is typically accepted as the objective is only to identify the tag and to know it is present inside a defined area [11]. In contrast, centimeter level accuracy is required in other applications, such as intelligent ressource management, supply and stock tracking in companies and personal medical monitoring in hospitals, which call for the use of UWB technology. In addition to consistent and high accuracy, research needs to further explore other RTLS design specifications such as reading range, object orientation-independent power, multipath mitigation ability, and detectability without prior knowledge of the target direction.

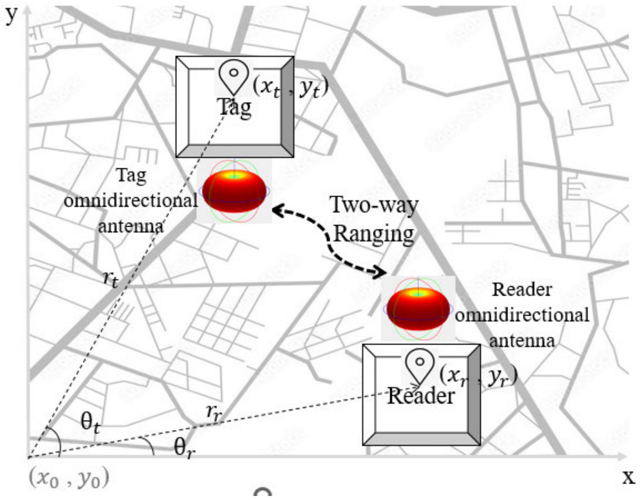

FIGURE 1. Conventional real-time locating system configuration.

First, the reading range of the RTLS must be investigated. Because the popularity of RTLS technology is typically for indoor use cases (from small surface retail centers to large warehouses where logistics need to be performed), the need to extend the reading range must be considered when choosing or designing the required RTLS. If this issue is considered from a broad perspective, the range depends first on the technology used for localization. If it is passive or semi-passive, such as RFID systems, then the achieved operating range will be limited to, typically, 10 m [12], as it mostly consists of passive tags, powered through wireless power transfer [13], [14]. However, if the technology is UWB, which mostly consists of battery-powered devices [15], the expected range can exceed 100 m, which is ten times greater than the current passive locating devices' range. If this issue is then considered from a more specific and smaller perspective, that is, with an already chosen technology in mind, the reading range depends deeply and mostly on the transmit power and link margin of the radio system. In this case, improving the transmit power fed to the front-end antennas would require either increasing the transmitter power itself or choosing an antenna with a higher gain compared to the state-of-the-art dipole-like antennas commonly used in indoor locating systems.

The next step of this study consists of the design of RTLS antennas. Indeed, these front-end components play a significant role in improving localization results, not only in terms of reading range through gain adjustment but also in the ability to enable object-orientation independent power [16] and multipath mitigation [17] through polarization adjustment (from commonly linear to circular polarization). Indeed, in [18], antenna polarization was taken into account to characterize the transfer function of UWB transmitting and receiving antennas. For this reason, their optimization should be considered, particularly when other devices and hardware in the RTLS architecture cannot be optimized nor changed at all. Recently, for this purpose, a novel circularly polarized ultrawide bandwidth high-gain antenna operating over two 500 MHz channels was proposed by the same authors [19]. Moreover, the importance of attenuating multipath components for UWB ranging applications was highlighted in [20], [21], [22], [23], and [24], thus, solutions such as the help of circular polarization in reducing these components need to be investigated.

Thus, the main contributions of this paper are:

- To demonstrate, through a real-scenario measurement campaign, the advantages of using the realized directional circularly polarized UWB patch antenna [19] in an available commercial RTLS system [25]. The measurements consist in ranging with an UWB tag and reader in outdoor and indoor environments.
- To highlight the advantages of using a directional circularly polarized antenna by the comparison of the achieved localization quality while employing the directional circularly polarized antenna, with its performance when using commercial omnidirectional linearly polarized dipole-like antennas. This comparison between the two cases, is made in terms of the reading range, object orientation-independent received power, and multipath mitigation.
- To investigate the effect of this antenna's characteristics on the reading range. For this purpose, an outdoor environment was privileged for the ranging measurements, to benefit of unlimited distance for tests. The results showed that the directional circularly polarized antennas achieve around 100 m of increased range compared to the linearly polarized antennas.
- To investigate the effect of the antenna's circular polarization on enabling the independence of the received power from the relative orientations of the reader and tag antennas. For this purpose, ranging was performed for different reader and tag orientations, and an indoor environment was privileged to ensure the validity of the results even in a complex environment, including walls and objects. The received power was found to be independent of the orientations of the reader and tag when using the circularly polarized antennas.

- To demonstrate the effect of the antenna's circular polarization on the attenuation of the multipath signals during ranging measurements. The results showed that, both in indoor and outdoor environments, the multipath is significantly reduced in the case of circularly polarized antennas compared to linearly polarized antennas.

The remainder of this paper is organized as follows. Section II describes the UWB locating architecture flow. Section III analyzes the employed UWB antenna design characteristics, followed by section IV in which the designed antenna results and a comparison with the commercial antenna are presented. Section V addresses the use case measurement campaign and scenarios, and discusses ranging measurement results in detail through a comparison study. Finally, the conclusions are presented in Section VI.

II. LOCALIZATION WITH RTLS TECHNOLOGY

Real-time locating technology allows the inference of highly accurate position information. It has emerged with the need to localize objects situated in harsh propagation environments, for example, trapped inside buildings or inside mines. Thus, it is employed in indoor scenarios characterized by the presence of multipath signals, reflections, and obstacles. To mitigate these problems and infer centimeter-level accuracy of the localization, RTLS is typically based on UWB signals, as they allow the precise measurement of the time-of-arrival (ToA) [9], from which the distance is then calculated during the received signal post-processing phase.

Fig. 1 illustrates the RTLS configuration considered in this study. It is composed of a reader-tag nodes couple that communicates through a two-way ranging (TWR) method, which resorts to ToA measurements to allow the reader to infer the tag's location.

A. RANGING METHOD

The TWR method allows for ranging, that is, distance estimation between the two nodes. However, to infer tag position estimates of coordinates (x_t, y_t), at least three readers performing ToA measurements are required. In contrast, there is an additional well-known method, that uses only one-way tag-to-reader communication to obtain position information, which is TDoA method. This technique also requires at least three readers and estimates the position of the tag by measuring the difference in the time at which the signal from the tag reaches these readers [9], [10], [26].

In this study, the objective is to highlight the advantage of using more suitable antennas (180° directional radiation antennas with UWB circular polarization) compared to commonly used UWB low-gain omnidirectional antennas with linear polarization, to improve the performance of the general RTLS in terms of reading-range, object orientation independent power and achieved multipath filtering. Consequently, we focus on the TWR method to estimate the distance r_t between the reader and tag, as this objective needs to be initially verified for one reader-tag couple configuration to further seek its implementation in more complex architectures that call for a higher number of fixed readers.

TABLE 1. Adopted instrumentation.

Reader	UWB transceiver	STMicroelectronics [25]
Tag	UWB transceiver	STMicroelectronics [25]
Antenna 1	Omnidirectional	STMicroelectronics [25]
Antenna 2	180° radiation	this work and [19]

B. INSTRUMENTATION AND CONFIGURATION

In this section, we describe the waterfall of the UWB RTLS system. Table 1 below lists the instrumentation components used during the ranging measurements.

1) TRANSMITTER

In this study, the reader transmits a 500 MHz bandwidth UWB interrogation signal. In the time domain, this signal is a pulse of frequency $f_c = 4\,GHz$ with a pulsewidth of $T_w = 3\,ns$ generated by the electronics board. The pulse is repeated with a period T_p and applied to an UWB antenna. According to STMicroelectronics documentation [25], the transmitted spectral power density measured at the antenna output has a peak level of $-36\ dBm/MHz$, which complies with the Federal Communications Commission (FCC) mask limits [4], [6], [7]. This limit is imposed on the effective radiated isotropic power (EIRP) and the antenna gain in the maximum direction of the transmitting antenna is considered [4], [10].

2) COMMUNICATION LINK

The tag antenna receives the interrogation signal, which enables the tag to transmit its response signal after a fixed reply delay τ_d of the transceiver module. The TWR method between the reader and tag is illustrated in Fig. 2, as explained in [9].

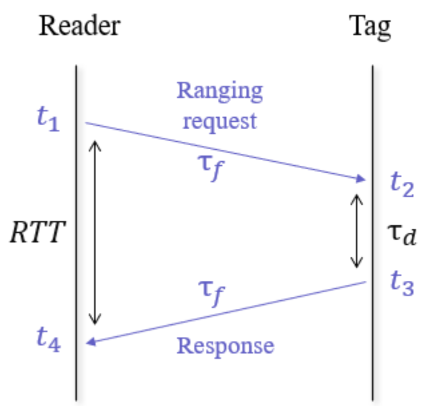

FIGURE 2. Two-way ranging principle.

3) RECEIVER

Because electromagnetic waves propagate in free space at a speed of light $c = 3 \times 10^8\ m/s$, it is possible to determine the distance between the reader and tag. The reader starts by having the instant t_1 time which is known to the module,

TABLE 2. European UWB lowband frequency channels.

Channel	Center frequency (MHz)	Bandwidth (MHz)
1	3494.4	499.2
2	3993.6	499.2
3	4492.8	499.2
4	3993.6	1331.2
5	6489.6	499.2

sends the request packet to the tag and, then awaits the signal to return after a round trip time (RTT) to obtain the time instant t_4. The response delay, τ_d is primarily known to the device. Therefore, the time of flight between the reader and tag can be obtained from the following equations [9]:

$$\tau_f = \frac{(t_4 - t_1) - \tau_d}{2} \tag{1}$$

$$RTT = t_4 - t_1 \tag{2}$$

Using the obtained time of flight τ_f, the distance can then be computed, and the ranging is finalized.

III. UWB ANTENNA DESIGN

The following section focuses on the antenna component and details the design motivation and steps.

A. ANTENNA DESIGN MOTIVATION

Typically, in the RTLS architecture based on UWB technology, as mentioned previously, both reader and tag antennas exhibit omnidirectional dipole-like radiation behavior. Indeed, this is a key enabler for large coverage because both nodes can detect each other regardless of their relative position. However, for most localization techniques, and their applications inside buildings, retail wear-houses, or industrial infrastructure, readers are mostly fixed on walls or any vertical surface of a device such as a machine or a robot that goes around the facility to track items. This is the case, for example, for RFID and RTLS solutions proposed by ''Kathrein'' or ''Turck Vilant'' companies [27], [28].

Fixing a device with an omnidirectional antenna on a vertical surface would not take advantage of this omnidirectionality because half of the radiated wave would be absorbed on the back surface. Starting from this point, the constraint of omnidirectional radiation could be lightened on antennas for RTLS system readers, as only a 180° coverage would be sufficient to detect tags in the surrounding environment. For this reason, a patch-type antenna, operating along two 500 MHz UWB frequency channels (channel 2 and 5) was proposed in [19].

For details regarding UWB channels allocation in the frequency spectrum, Table 2 illustrates the lowband frequency UWB channels' information, among which the channels mentioned in this paper are allocated.

As observed, UWB channel 2 is centered at 4 GHz (3.75 GHz to 4.25 GHz), and channel 5 is centered at 6.5 GHz (6.25 GHz to 6.75 GHz). Thus, if desired, the initial antenna in [19] could be frequency reconfigured through p-i-n diodes to choose on which channel to operate, giving it the capability to adapt to different commercial RTLS UWB-based electronics modules provided for localization, which might not be designed to work on the same UWB channel. Furthermore, this antenna has the particularity of being circularly polarized along the UWB bandwidth of each channel enabling object orientation-independent ranging.

To accommodate the commercial RTLS and UWB localization module used for measurements (the B-UWB-MEK1 evaluation module [25] from former BeSpoon company, acquired recently by STMicroelectronics), which operates by default on channel 2, this channel was chosen as the channel along which the new antenna will be designed to operate.

Furthermore, because antenna frequency reconfigurability is not necessarily needed here, a simplified one-channel version of the previous antenna was designed and fabricated to operate along channel 2 and will be used on both reader and tag sides in the measurement campaign demonstrated below in this paper. In the following, we detail design method, characteristics, and results of the channel 2 antenna.

B. ANTENNA DESIGN

The objective of the design was a high-gain, UWB antenna with circular polarization and 180° radiation coverage. The design steps are summarized as follows:

- To achieve relatively high gain and 180° coverage, a patch-type antenna was chosen.
- Subsequently, a capacitive feed and coupling method was employed to achieve UWB impedance matching over the requested channel.
- Finally, a directional coupler was integrated into the bottom substrate layer to obtain circular polarization along the achieved antenna bandwidth.

The initial frequency reconfigurable antenna [19] profile is illustrated in Fig. 3 and the new simplified version (one-channel), designed here, is shown in Fig. 4. The adopted capacitive feed technique [29] is aimed at probe-fed patch antennas, and consists of exciting a small element placed on the same substrate layer as the radiating element and at a gap distance from it. The dielectric substrate was suspended in air as shown in Fig 3.

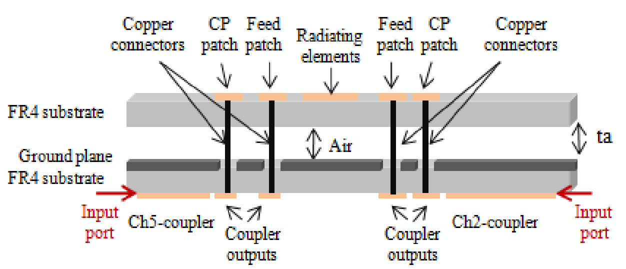

FIGURE 3. Side view of the frequency reconfigurable UWB antenna [19].

As illustrated in Fig. 4, the new antenna is composed of only one radiating element and one coupler both designed at the center frequency $f = 4\ GHz$. The dimensions of the radiating element are $W = L = 23\ mm$ and were derived

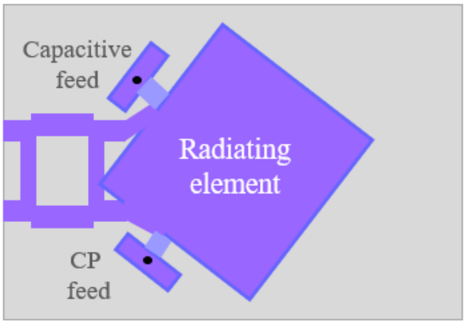

FIGURE 4. Simplified circular polarized antenna version, operating on one UWB channel, with radiating element (top layer) and directional coupler (bottom layer).

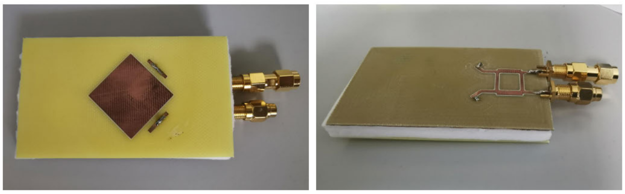

FIGURE 5. Prototype of the circularly polarized antenna operating over UWB channel 2.

from the standard patch antenna design. The two capacitive feed lines ensure two orthogonal feeds and thus circular polarization. They are both of width $wf = 1.6\ mm$ and placed at a gap distance from the radiating element $d = 2\ mm$. These two lines are both fed by vias attached to the coupler outputs which are situated at the bottom substrate. The vias start from this substrate and go through the ground plane, the air gap (ensuring bandwidth), and finally to the upper substrate.

IV. ANTENNA SIMULATION AND EXPERIMENTAL RESULTS

This section presents the performance of the antenna achieved by the simulation and measurements in terms of:

- Reflection coefficient (impedance matching) along the frequencies of UWB channel 2.
- Directivity and gain.
- Radiation pattern.
- UWB circular polarization along 180° coverage.

These results will allow the implementation of this antenna in the RTLS architecture for performing ranging measurements.

The circularly polarized UWB antenna operating in channel 2, was fabricated using FR4 substrate of height 0.8 *mm* for both substrate layers. The antenna prototype is shown in Fig. 5. The air gap betweeen the ground plane and the upper substrate was replaced by foam whose dielectric constant is the same as that of air. The structure has two input ports, which are the inputs of the coupler, one of which is isolated during measurements using a 50 *ohm* match load.

A. UWB IMPEDANCE MATCHING

Fig. 6 shows the result of the simulated and measured reflection coefficient of one of the antenna ports $S11$ with

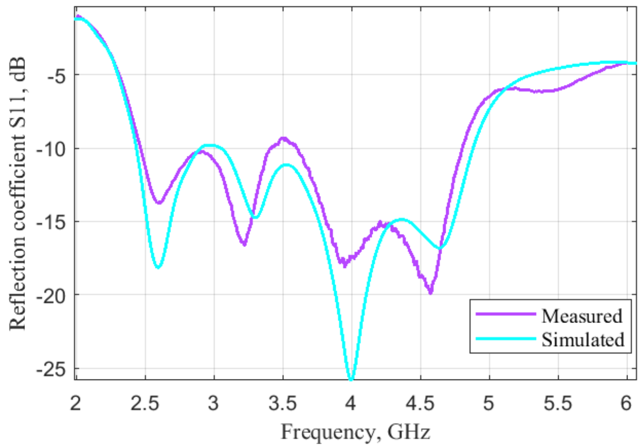

FIGURE 6. Antenna reflection coefficient.

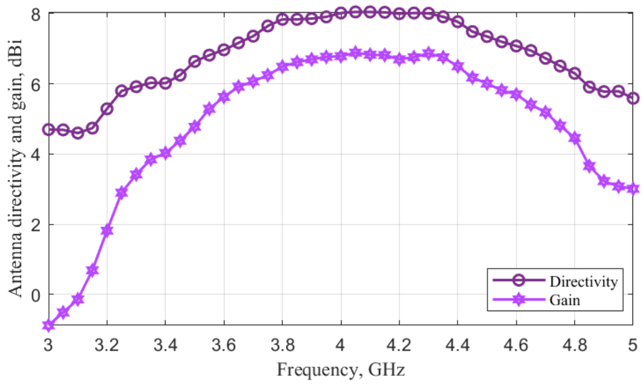

FIGURE 7. Measured antenna directivity and gain over the UWB channel 2 frequencies.

respect to the frequency, with the chosen air gap height $h_{air} = 7\ mm$. With reference to $-10\ dB$, the antenna impedance is matched along a bandwidth covering all UWB channel 2 frequencies. Furthermore, it can be observed that the antenna bandwidth covers more frequencies than the actual channel bandwidth, as it starts around 2.5 *GHz* and extends until around 4.8 *GHz*, this is a result of the chosen air gap height of 7 *mm* as this value is not the minimum limit value to achieve the 500 *MHz* range. This choice was made to cover the maximum bandwidth possible for other future use of the antenna and was not related to any other restrictions.

B. DIRECTIVITY AND GAIN

The antenna was measured in an anechoic chamber and Fig. 7 shows the resulting measured antenna directivity and gain with respect to frequency. The observed gain is of approximately 6.5 *dBi* and is stable along all channel 2 frequencies (3.75 to 4.25 *GHz*). The directivity follows the same curve but is naturally higher than the gain, maintaining a value of 8 *dBi* along the channel frequencies. It must be pointed out that maintaining a stable gain along all the desired channel frequencies is important for UWB antennas to exhibit the same behavior while operating with UWB electronic devices.

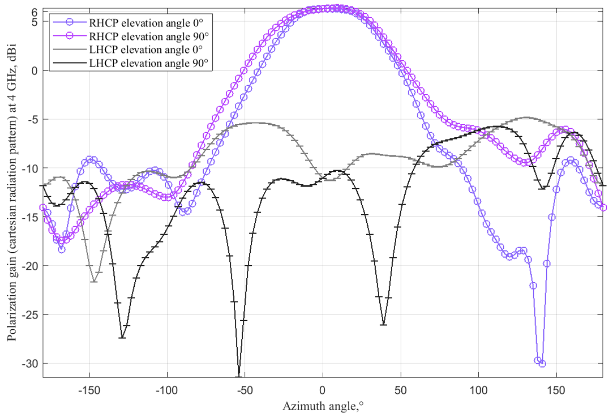

FIGURE 8. Measured azimuth antenna radiation pattern (polarisation gain) at center frequency 4 GHz, for elevation angles 0° and 90°.

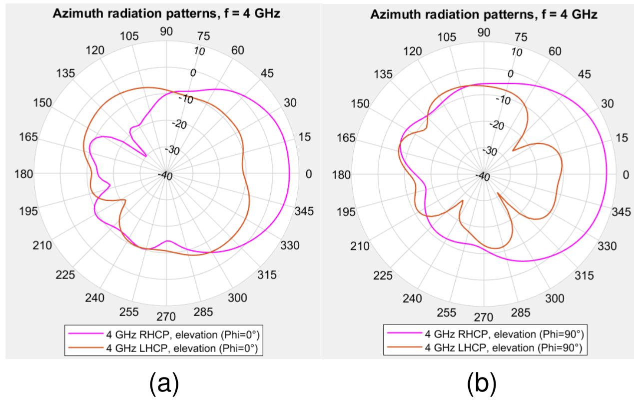

FIGURE 9. Designed circularly polarized antenna's measured radiation pattern at frequency 4 GHz (polar). (a) Elevation 0° (b) Elevation 90°.

C. RADIATION PATTERN AND CIRCULAR POLARIZATION

The measured radiation pattern is presented in terms of the polarization gain in the azimuth plane and plotted in Fig 8 and Fig 9. This radiation is measured at the center frequency $f = 4\ GHz$ varying the azimuth angle, for two elevation angles 0° and 90°. As shown in Fig. 8, the circular polarization of the antenna is right-handed (RHCP) because this polarization component has a superior gain of 6 dBi along the main direction of the radiation (around azimuth 0°). The cross-polarization, that is, the left-handed (LHCP) polarization, is at least $-10\ dB$ lower for any azimuth direction between $-50°$ and 50°.

D. COMPARISON WITH COMMERCIAL ANTENNA

The purpose of this work is to design a more suitable antenna optimized for real-time localization UWB commercial devices. A comparison with a commercial antenna belonging to the UWB evaluation kit from BeSpoon company (recently STMicroelectronics) [30] is reported in this section.

The radiation patterns of the designed and commercial antennas are shown in Fig 9 and Fig 10 respectively. First, we observed the radiation behavior of the designed antenna through the radiation of its dominant RHCP polarization. It can be observed that the antenna radiates directionally with 180° coverage. It specifically maintains a high gain of 6 dBi along 70° azimuth centered at 0° for both elevation planes (0° and 90°, as shown in Fig. 9.a and 9.b respectively). Back lobes are suppressed on the back surface of the antenna to less than $-8\ dB$.

As shown in Fig. 10, as the commercial antenna is linearly polarized (vertical polarization), it has E-plane and H-plane radiations. We intuitively associate its E-plane to the elevation plane and its H-plane to the azimuth plane. As the designed antenna radiation was traced with varying azimuth, we compare Fig. 9 RHCP radiation to the commercial antenna H-plane in Fig. 10 (varying azimuth, shown on the right figure). It can be observed that the commercial antenna for channel 2 has omnidirectional radiation along 360° with a gain of 2 dBi. Conversely, for the same gain, the designed antenna exhibits directional radiation along 95° azimuth. However, it has a higher gain along 70° in the azimuth plane, which includes the main directions of radiation when the antenna is fixed to a wall or vertical surface. The main differences between the antennas are presented in Table 3.

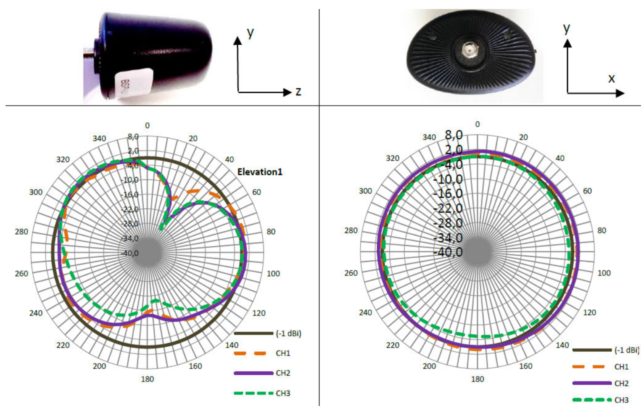

FIGURE 10. Commercial linearly polarized antenna's measured radiation pattern at channel 1, 2 and 3 [30].

V. MEASUREMENT CAMPAIGN AND RESULTS

The experimental setup and measurements are presented in detail in this section. The objective is to demonstrate the improved efficiency of an RTLS using TWR method, to locate a tagged object by adjusting the antenna specifications to the localization method's needs. A measurement campaign was conducted using the STMicroelectronics UWB transceiver as an anchor and tag, and TWR between the two was performed in two cases: first, employing typical commercial UWB omnidirectional monopole antennas with linear polarization, and then, employing UWB directional patch antennas with circular polarization. Measurements were repeated with the two antenna types for two different environments, outdoor and indoor, depending on the studied parameter (reading range, object orientation independence, and multipath mitigation). Finally, both antenna cases are compared and improvements are discussed.

TABLE 3. Antennae radiation comparison.

Antenna 1 (commercial)	Antenna 2 (this work)
UWB channel 2	UWB channel 2
Coverage (360° azimuth)	Directional cov. (70° azimuth @ 5 dBi)
Low gain (2 dBi)	High gain (6 dBi @ 60° azimuth)
Linearly polarized	Circularly polarized

The different characteristics of the antennas employed in these measurements are reported in Table 4 and, more specifically, in Table 3.

A. OUTDOOR SCENARIO FOR READING-RANGE

Although RTLS localization specializes in locating objects indoors because of its robustness to harsh propagating environments, this part of the measurements was realized in an outdoor environment because of space constraints inside buildings, in order to estimate the maximum reading range of the RTLS at hand, for the two employed antenna types. For this measurement, the transceiver tag was placed in a fixed position, and the transceiver reader was moved. The approach is to start with the reader as close as possible to the tag and then move away until the reader can no longer detect the tag; thus, it is no longer outputting the ranging results. These ranging results appear on the computer to which the reader is attached as data acquisition is possible through UART on USB, which is also used to power the reader. The tag is powered by a power bank unit. The obtained results of ranging are as follows:

- The time between measurements in milliseconds, knowing that for the TWR mode, the transceiver is able to make a number of measurements up to $204/s$.
- Device ID of the reader board itself.
- Device ID of the tag board.
- The link quality indicator (LQI), which is the ratio of the measured received signal strength to the already known saturation signal strength of the transceiver, it is computed as a percentage.
- The corresponding reader-tag distance in meters.

Figure 11 illustrates the measured LQI with respect to the measured distance while moving further away from the tag.

Although the objective is to evaluate the performance range-wise, for clarity, the reading range is plotted on the horizontal axis. Indeed, it is easier to observe that the measured maximum reading distance is 82 m when using the commercial linearly polarized (LP) omnidirectional antennas, whereas it is 175 m when using this work's directional CP patch antennas. Thus, an important difference of almost 100 m in the maximum reading range was obtained owing to the antenna gain improvement.

It is important to note that, even in line-of-sight (LOS) conditions, the environment and the initial position of the fixed tag or the position of the mobile reader during the campaign leads to variations in the measurement results, such as the maximum range obtained, due to the random nature of

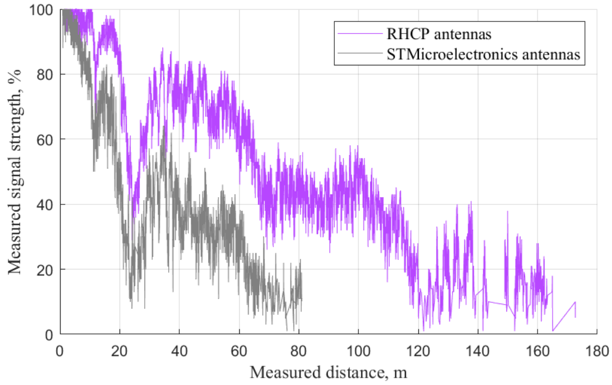

FIGURE 11. Reading range of the RTLS. Comparison with the commercial antenna.

the radio propagation channel. This is to highlight that, for example, the maximum range obtained with the commercial transceiver and antennas here of 82 m is indeed different from the datasheet, which claim a maximum range of 600 m, as typically this value is obtained either theoretically or through LOS measurements within a better propagating environment to obtain the best result possible. In contrast, the measurements in this study were performed in a completely realistic and imperfect outdoor environment. Indeed, other measurement campaigns that we performed with commercial transceivers and antennas were able to exceed 85 m and achieved a maximum range of approximately 120 m in a real environment, which is still significantly lower than the 175 m achieved by the designed antenna. In conclusion, to compare the performance of RTLS parameters such as range, it is essential to ensure that the experimental setup and environmental characteristics are as closely matched as possible to obtain accurate comparable results.

B. INDOOR SCENARIO FOR OBJECT ORIENTATION INDEPENDENCE

The objective of the following experiment is to detail and verify the robustness brought to the RTLS by the circular polarization characteristics of the designed antennas. This robustness is mainly against two hindering factors in radio propagation, namely, the multipath signals due to reflections against surfaces or objects, and the received signal attenuation due to polarization mismatch between reader and tag (which depends on tag-reader relative orientation).

The reason why an indoor scenario was preferred for this experiment is that the RTLS has to prove itself robust in a harsh environment (presence of objects and obstacles), as this would mean it will also have good performance in outdoor scenarios that tend to have fewer constraints, such as the absence of walls.

The considered indoor environment was the corridor of the LEAT laboratory that is 50 m long. The tag was mobile and the reader was fixed at one corridor end. Steps of 15 m were set using a laser telemeter to determine the true absolute distances at which the ranging measurements were taken.

TABLE 4. Antennae characteristics.

Antenna / Characteristics	Frequency range	Reflection coeff.	Gain	Radiation	Polarization type
Antenna 1 (commercial [25], [30])	$2 - 4.77\ GHz$	$< -8\ dB$	$2\ dBi$	Omni directional	Linear (vertical)
Antenna 2 (this work and [19])	$3.75 - 4.25\ GHz$	$< -10\ dB$	$6\ dBi$	180° directional	UWB Circular (Right-hand)

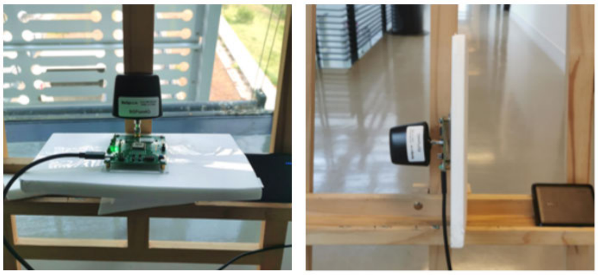

FIGURE 12. Two-way ranging with the commercial antenna, characterized by 360° omnidirectional radiation and linear polarization.

FIGURE 13. Two-way ranging with the designed antenna, characterized by 180° directional radiation and circular polarization.

The reader antenna is kept on a ''vertical'' configuration and the tag antenna orientation is first set to vertical (0°), and then changed to horizontal (90°) orientation.

Fig. 12 and 13 illustrate the orientation configurations of the two antennas, the commercial linearly polarized antennas and designed circularly polarized patch antennas, respectively.

To measure the polarization-mismatch independence of the received power between the reader and tag, a comparison between the LQI results obtained by ranging (that is, distance measurement) with reader-tag antenna co-orientation and cross-orientation is required. The following steps are followed for each distance point:

- Measurement of the LQI (by ranging) with reader and tag antennas having the same orientation d_{cop} (for example, vertical reader - vertical tag).
- Measurement of the LQI with reader and tag antennas with orthogonal orientations d_{crossp} (for example, vertical reader - horizontal tag).

Fig. 14 illustrates the LQI as a function of the measured distance for the different antenna cases. LQI is proportional to the received power. These results were obtained by ranging indoors to up to 35 m, with the reader antenna always fixed in a vertical orientation.

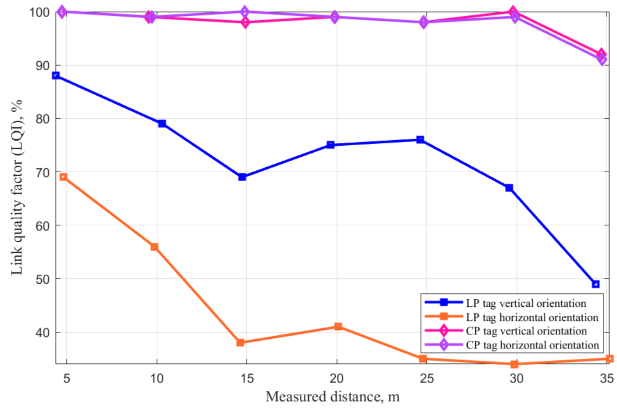

FIGURE 14. Object orientation-independence of received power, comparison between linearly and circulary polarized antennas. Reader antenna always in vertical orientation.

By comparing the LQI achieved in the figure, it can be observed that, in the case of the circularly polarized reader and tag antennas, the LQI (and thus the received power) is almost identical at all distances, regardless of the orientation of the tag antenna, that is, regardless of wether it's the same as the orientation of the reader antenna.

Differently, in the case of linearly polarized antennas used in both the reader and tag, the received power is very different between co-polarization and cross-polarization cases (blue and orange curves), along all distances. Here, the difference between their LQIs varies between 20 % and 50 %. This is a significant amount of power attenuation caused by polarization-mismatch, which greatly deteriorates the RTLS performance, as some objects may not be detected if their antennas is not oriented in the same orientation as the reader antenna.

It is important to note that polarization-mismatch induced power attenuation (which can occur if the antennas are linearly polarized and have cross-orientations), for longer distances, especially closer to reader sensitivity, can also negatively affect the reading range.

It can also be observed in the same figure that the LQI achieved by the circularly polarized antennas is always ≈ 20 % higher than the LQI obtained in the best case scenario of linearly polarized antennas (ie. both the reader and tag antennas vertical). This difference is mainly owing to the higher gain of the designed directional antennas.

C. MULTIPATH MITIGATION WITH CIRCULAR POLARIZATION

Fig. 15 illustrates further indoor and outdoor ranging measurements, where the objective is to investigate wether

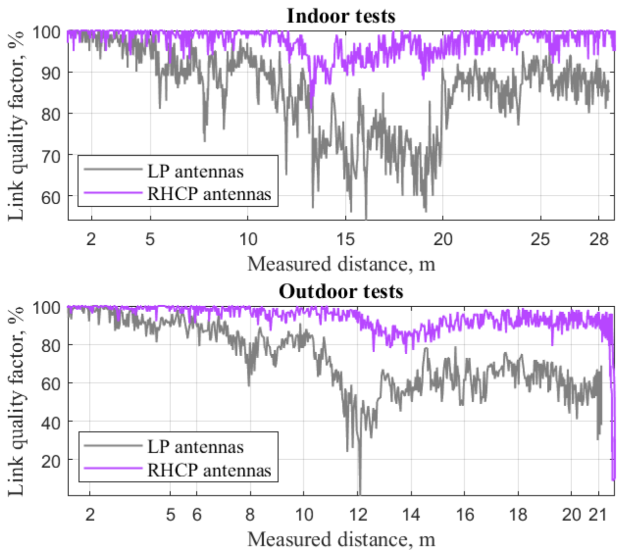

FIGURE 15. Multipath and antenna gain effects on received signal strength in ranging.

circular polarization helps mitigate multipath reflection signals, which tend to be more prevalent in indoor environments because of the presence of walls and usually more objects. Behind the reasoning that circular polarization reduces the number of multipaths, is that if the transmitting and receiving antennas both have same-sense circular polarization (here, right-hand sense), the receiver antenna filters out reflected signals from metallic surfaces as they are reflected with circular polarization of opposite-sense [17]. Furthermore, multipath is undesired in localization applications because of the possibility of path-overlap [31], which consists of reflection signals overlapping with the first direct-path signal, from which the time-of-arrival is computed. This path-overlap would then cause non-recognition of the direct path signal which will lead to errors in the time-of-arrival measurement and thus errors in distance estimation.

Thus, we evaluate the LQI curves, obtained through ranging, to determine the multipath effect on the ranging measurement and compare it between the two antenna cases, with linear and circular polarizations.

From the results shown in Fig. 15, the curves of the linearly and circularly polarized antennas follow almost the same high-and-low patterns at the same distances, in both indoor and outdoor measurements. This is because the same multipath signal components were present at these distances (that is, identical environment at each distance). Thus, this multipath will affect the propagation in the same manner for both antenna types, indoors and outdoors. Furthermore, if we compare the linearly polarized antenna curve with the circularly polarized antenna curve (both indoors and outdoors), it can be observed that the LQI and thus received power dips and peaks are less significant and have a low level of variation when using circular polarization compared to linear polarization. This observation demonstrates that circular polarization with the same direction (here, Right Hand) in both reader and tag antennas helps to filter reflections, precisely those that arrive with opposite circular polarization (here, Left Hand). This can be observed for both the indoor and outdoor cases.

VI. CONCLUSION

This paper investigated the positive effects and advantages of using directional circularly polarized UWB antennas to improve RTLSs in terms of the reading range, object-orientation independent received power, and multipath mitigation. Real-environment measurements were conducted in indoor and outdoor scenarios using a commercially available RTLS. The results demonstrate that the reading range was improved in the case of the designed directional antennas compared to conventional omnidirectional UWB antennas by almost 100 m owing to the higher gain, as well as to the suppression of the cross-polarization mismatch effect on the received signal strength by circular polarization. Object-orientation independent received power was also observed in the case of circularly polarized antennas, especially in harsh indoor environment. In contrast, power attenuation caused by polarization mismatch was observed in the case of linearly polarized antennas. Furthermore, circularly polarized antennas were observed to help multipath mitigation in both indoor and outdoor scenarios, as the LQI curves demonstrated less harsh variations compared to linearly polarized antennas. Thus, we conclude that locating systems can be significantly improved through directionality and circular polarization of antennas compared with the currently widely used omnidirectional linearly polarized UWB monopole antennas. The type of antennas presented in this work can not only improve time-based locating systems, such as the system employed here, but also received signal strength indicator (RSSI) based locating technologies, such as RFID locating, as it would help increase the power and thus help additionally provide precise localization information.

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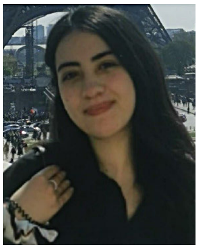

AMINA BENOUAKTA (Student Member, IEEE) received the B.S. degree in electronics, electrotechniques, and automation, and the M.Sc. degree in components and systems for telecommunications from the University of Montpellier, France, in 2018 and 2020, respectively. She is currently pursuing the Ph.D. degree with the Laboratory of Electronics, Antennas and Telecommunications, University Côte d'Azur, Sophia Antipolis, France. After an exchange year of M.Sc. with the Norwegian University of Science and Technology, Trondheim, Norway, in 2019. Her research interests include the conception of antenna systems destined for the Industrial Internet of Things objects' flux monitoring and precisely for indoor localization using different technologies and notably ultra-wide bandwidth communications.

FABIEN FERRERO (Member, IEEE) received the Ph.D. degree in electrical engineering from Université Nice-Sophia-Antipolis, in 2007. From 2008 to 2009, he was with IMRA Europe and with the Aisin Seiki Research Center, as a Research Engineer, where he developed automotive antennas. In 2010, he was an Associate Professor with the Polytechnic School, Université Nice-Sophia-Antipolis. Since 2018, he has been a Full Professor with Université Côte d'Azur. He is doing research with Laboratoire d'Electronique, Antennes et Telecommunications. His research interests include the design and measurement of millimetric antennas, the IoT systems, and reconfigurable antennas.

LEONARDO LIZZI (Senior Member, IEEE) received the M.Sc. degree in telecommunication engineering and the Ph.D. degree in information and communication technology from the University of Trento, Italy, in 2007 and 2011, respectively. During the Ph.D. degree, he was a Visiting Researcher with The Pennsylvania State University, University Park, PA, USA, and with the Nagasaki University, Japan. From 2011 to 2014, he was a Postdoctoral Researcher with the Laboratory of Electronics, Antennas and Telecommunications, Université Côte d'Azur, Sophia Antipolis, France, where he has been a Maître de Conférences (Associated Professor), since 2014. His research interests include reconfigurable, miniature, multistandards antennas for the Internet-of-Things applications, wearable devices, and 5G terminals.

ROBERT STARAJ (Member, IEEE) was born in Antibes, France, in 1965. He received the Ph.D. degree in electronics from Université Nice-Sophia-Antipolis, France, in 1992. In 1993, he joined École Supérieure d'Ingénieurs de Nice-Sophia Antipolis (ESINSA), and the Laboratory of Electronics, Antennas and Télécommunications-CNRS UMR7248 (LEAT), as an Assistant Professor. He was the Director of GDR Ondes-CNRS, French National Research Group on Waves, from 2014 to 2017, and the Assistant Director of LEAT. After being the Head of the CMA Research Group, Conception et Modélisation d'Antennes—Antennas Design and Modeling, LEAT during several years, he is currently the Director of LEAT. Since 2003, he has been a Full Professor with Polytech Nice-Sophia, École Polytechnique de l'Université de Nice-Sophia, and an In-Charge of the Telecommunications and Networks Speciality, Department of Electronics. His research interests include printed antennas and arrays, active, integrated, adaptative, and miniature multistandard antennas for wireless, RFID, MIMO systems, and biomedical applications.