Antennas for Object Localization Systems

João Vasco Carreira
joaovrcarreira@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

The objective of this work is to study different localization techniques, technologies and antennas in order to find a suitable solution that can be integrated in an indoor localization scenario. The antenna proposed on this paper is a Sectorised Antenna Array (SAA) that consists of four printed Circular Disk Monopole (CDM) Antennas as reference elements and a metallic reflector. The reference element antennas are impedance matched to 50Ω ports in the whole UWB band from 3.1 GHz to 10.6 GHz, as defined by the FCC. A low profile and compact solution was achieved for the reference elements with total height and width of 38.7 mm and 37.8 mm, respectively, printed on an FR-4 dielectric substrate with 0.121 mm of thickness. Regarding the CDM Antenna Array, the simulated reflection coefficients show a resonance at the ISM 5.8 GHz band, which was chosen as the band of interest for a possible localization application. The antenna was tested in free space and 16 S-parameters were measured and the results were confronted with simulations, resulting in minor differences only. The CDM Antenna Array is proposed aiming at making the antenna as compact as possible and still achieve 360° coverage in the azimuth plane. Additionally, the results suggest that an appropriate algorithm could point the main lobe in the desired directions, anticipating the possibility of realizing a scanning array.

Keywords: Compact antennas, sectorised antenna array, ISM band, UWB, localization systems

1. Introduction

Antennas can be considered as an important factor in the evolution of localization systems since these systems are consisted by sensors and targets. For different localization techniques, different antenna bandwidths and configurations are required, depending on if the antenna is the sensor, the target, or both. For these techniques, there are non-radio-frequency (non-RF) and radio-frequency based (RF) technologies. Radio-frequency based technologies such as Ultra-wideband (UWB) and Ultra High Frequency Radio Frequency Identification (UHF-RFID) are the most efficient for this matter in the current state of the art, although, other technologies will be studied as well.

Good localization implies high precision and ranging, thus UWB is used on Impulse-radio. The performance of localization systems based on Impulse-Radio is affected by the pulses shape. Impulse radio communicates with very short duration pulses and considerably low energy. The antennas have to be designed considering the properties that characterize them in steady state such as the radiation pattern, linear phase and stable impedance, reflection coefficients but it is also relevant to study the transfer functions in the pulses’ bandwidth in order to obtain high value of impulse fidelity and to prevent high impulse dispersion. It is also very important to study the influence of nearby objects and the resilience to body influence.

The main goal of this work is to find a suitable antenna solution that can be integrated in an indoor scenario using different localization techniques.

2. Indoor Localization Systems

When talking about indoor localization it is certainly important to debate the environments they are established to work. There are several techniques, technologies and applications that must be taken into account in order to design the infrastructures for an environment. Although there is no standardization on how the antennas must be placed in an indoor environment, there are some common models. According to the study at [2] a few examples of typical scenarios are briefly presented.

2.1. Environment Models

A typical model is based on the use of several omnidirectional antennas, depicted in Figure 1, and is most efficient when used with the lateration or fingerprinting techniques, which are described next, in section 2.2.

A distinct model best suited for directive antennas and used with the proximity technique is com-
commonly implemented on RFID systems. This model is illustrated in Figure 2 and is characterized by the use of directional antennas that have narrow radiation beams in order to achieve decreased interference from other tags.

Figure 2: Directive antennas based environment model. RFID scenario example.

A further model, appropriate for SAA is presented in Figure 3. This model commonly uses the Angle of Arrival technique since the localization process is usually done by analyzing the received signal from directive elements or by performing a sweep of the radiation beam. This scenario takes advantage of the SAA high coverage area, multi-path rejection and mainly the reduced necessity of reference units.

Figure 3: SAA based environment model with four sectors. Each antenna from the array covers a sector.

Lastly, a model based on phased arrays is shown at Figure 4. Similarly to the SAA based model, the Angle of Arrival technique is also used since the localization process is done by performing a sweep of the radiation beam. This scenario takes advantage of the phased arrays’ high coverage area and improved signal-to-noise ratio.

Figure 4: Phased array based environment model where the radiation beam covers the whole area.

2.2. Localization Techniques

In order to determine the location of a target relative to one or to several reference points, parameters like the angle and distance must be measured. These measurements lead to the possibility of determining the target’s location, which may be done using different techniques. These techniques have different characteristics and may be chosen depending on the desired accuracy and the context of the application. As so, various techniques have been developed in order to mitigate the measurement errors.

2.2.1 Triangulation

The triangulation technique is based on the basic geometric properties of triangles to determine the target’s location and has two derivations known as Lateration and Angulation. Lateration, which is also known as multilateration or trilateration, depending on the number of reference points necessary for the estimation, is range based and uses distance measurements of multiple reference points to estimate position. On the other side, angulation is angle based and measures angles relative to points with known orientation in order to estimate the location.

Lateration. In Lateration, the distance can be determined through different methods that include computing the signal propagation time of flight (ToF). The methods given special attention here are the Time of Arrival (ToA), Time Difference of Arrival (TDoA), Round-Trip Time of Flight (RTToF).

Time of Arrival (ToA). Time of arrival measures the distance by computing the signal propagation time between the transmitter and the receiver. A representation of this method is presented in Figure 5 as an example.

Time Difference of Arrival (TDoA). The distance is measured by computing the time difference of the propagation between at least three reference points
with the target. An illustration of this technique can be seen in Figure 6.

**Figure 5:** ToA technique with 3 reference points.

**Round-Trip Time of Flight (RToF).** This method works in a similar way to a radar apart from the target unit on RToF performing signal processing while at radar it is only reflected back. RToF measures the time of flight of the signal propagating between the transmitter and the target and back to the transmitter. An example of this method can be seen in Figure 5 (except the signal travels two times in RToF).

**Angulation.** This triangulation derivation is often known as Direction finding (DF) and fewer times as Direction of Arrival (DoA), or Angle of Arrival (AoA).

**Angle of Arrival (AoA).** The location estimation must be done having at least two reference points and two measured angles in order to be able to locate the target in the 2-D plane, and three of each for the 3-D plane. The location is then estimated by intersecting multiple angle direction lines as shown in Figure 7. The most efficient antennas for this purpose are antenna arrays or directive antennas.

**Figure 6:** Representation of the TDoA technique.

**Figure 7:** Representation of the AoA technique with 3 reference points.

**Figure 7:** Representation of the AoA technique with 3 reference points.

**2.2.3 Proximity**

The proximity technique is somewhat simple comparing with the other techniques described, and unlike them, only a relative location information is achievable. The location is determined as a result of knowing the exact position of the sensor antennas. When the mobile target is detected by the sensor its position is linked to the sensor’s position, and if more than one sensor detects the target, it is linked to the closest stronger received signal sensor, as illustrated in Figure 8.

**Figure 8:** Illustration of the Proximity technique used on a Cell-ID scenario.

**2.2.4 Fingerprinting**

Fingerprinting is used on a scene analysis algorithm that collects the characteristics of that scene, which are called fingerprints, and then computes the location of the target by correlating the online measurements with the stored fingerprints.

**2.3. Localization Technologies and Applications**

The referred techniques can be used by several technologies which can be based on radio-frequency or not. Non radio-frequency include Optical or Ultrasound based technologies whereas the radio-frequency technologies and wireless infrastructures
to be discussed are Wireless Local Area Networks, Wireless Personal Area Networks, Wireless Body Area Networks, Ultra High Frequency Radio Frequency Identification and Ultra-Wideband. Special attention is given to UHF-RFID and UWB whereas further information on the other technologies can be seen at [7], [3] and [5].

2.3.1 Ultra High Frequency Radio Frequency Identification

The Radio Frequency Identification (RFID) is a low cost localization technology that is progressively becoming more popular and a possible replacement for the barcode technology, for instance. Although it can operate at other frequency bands, a particular interest is given to the Ultra High Frequency (UHF) band, which ranges between 860-960 MHz. This technology consists of a reader antenna and a tag, which can be active or passive, depending on if it contains a battery or needs an external power source in order to transmit signals. The performance of the RFID system will be defined by the performance of the tag since it is the device that carries the data [8]. A microchip and an antenna are included in the tag and require a connection and good power transmission between them. This technology’s major advantage is not requiring LoS between the tag and the reader. Additionally, it also provides high data rate, security, cost effectiveness and compactness [6].

2.3.2 Ultra-Wideband

Systems using ultra-wideband (UWB) antennas follow some regulations concerning the frequency range. The agreed UWB definition is established to operate in a bandwidth over 500 MHz or at least 20% of the center frequency. The UWB spectra are not licensed, therefore, a maximum radiated power of -41.3 dBm/MHz effective isotropic radiated power (EIRP) is set in order to avoid interference with other systems [1]. Thus, there are international regulation standards, the European Commission allocated a band from 6 GHz to 8.5 GHz [9], and on the other hand, the Federal Communications Commission (United States) allocated an ultra-wide bandwidth of 7.5 GHz where the frequency ranges from 3.1 to 10.6 GHz. Contrary to the previously described technologies, UWB requires very low transmitting power since the information is transmitted in the form of short pulses in order to occupy the most of the bandwidth. As a result of this, systems using UWB can have longer battery life and reduced multi-path channel fading [4].

3. Printed UWB Antenna for Localization Systems

The main goal of this work is to develop an antenna that can be used with localization systems. This section covers all the steps taken in the design, simulations and measurements of the proposed CPW fed Circular Disk Monopole Antenna.

3.1. Circular Disk Monopole Antenna Geometry

The chosen geometry for the antenna proposed in this work can be seen in Figure 9. The classical monopole with a circular disk radiating patch design was preferred due to its good performance regarding the necessary conditions, in order to be used with a localization system, summarized below:

- Low profile
- $|S_{11}| \leq -10$ dB for good impedance matching in the desired band
- High gain for maximum radiated power
- Omnidirectional radiation pattern or as close as possible

![Figure 9: Base model geometry with studied parameters.](image)

The antenna will be referred to as CDM (Circular Disk Monopole) antenna and was initially modelled in an FR-4 dielectric substrate. The current distribution on the metallic surface of the CDM was analyzed in order to understand how the chosen geometry will affect the antenna’s characteristics.

From the UWB frequency range, the antenna was studied in the 3.5 GHz frequency because it is an antenna resonance and 5.8 GHz because it is an ISM band of interest.

Observing Figure 10 it is possible to see most of the current comes from the feeding line, as it should, and follows the feeding strip up to the radiating patch, flowing along the margins, which means the...
feeding line width and the radius of the disk will be important parameters. There is also current concentrated on the top edges of the ground plane and on the sides near the feeding strip, thus the width and length of the ground plane and the gaps between the ground plane and the radiating patch and between the ground plane and the feeding strip must also be taken into account. These parameters are shown in Figure 9.

Figure 10: Simulated surface current distribution of the CDM antenna.

The CDM antenna is CPW-fed and has a single metallic layer. The feeding technique is important for impedance matching which will ensure the maximum possible power is transmitted. The analytical line impedance value of 50Ω was calculated in CST Microwave Studio™ when studying the effects of the feeding strip width and the gap between the ground plane and the feeding strip. The antenna is excited using a SMA connector.

3.2. Simulation Results

The antenna dimension’s parameters were optimized with the optimizer tool present in CST Microwave Studio™. The final optimal values for the proposed CDM antenna are presented in Table 1.

Table 1: CDM antenna final parameter values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [mm]</th>
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<tr>
<td>Wg</td>
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</tr>
<tr>
<td>L</td>
<td>38.7</td>
</tr>
<tr>
<td>Lg</td>
<td>9</td>
</tr>
<tr>
<td>Wf</td>
<td>3</td>
</tr>
<tr>
<td>g</td>
<td>0.35</td>
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<tr>
<td>gp</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>11.475</td>
</tr>
</tbody>
</table>

3.2.1 Reflection Coefficient

The simulated return loss for the proposed CDM antenna is presented in Figure 11. The results show that the $|S_{11}|$ parameter is below -10 dB for most of the frequency range, which means the impedance matching is good. Moreover, the bandwidth covers the whole range of the FCC UWB band from 3.1 GHz to 10.6 GHz. Additionally, it is also possible to see the antenna’s resonances at 3.5 GHz and at 9.7 GHz.

Figure 11: Simulated $|S_{11}|$ parameter of the proposed CDM antenna.

3.2.2 Radiation Pattern and Efficiency

The radiation pattern plots of greater interest are calculated in terms of $\theta$ for $\phi = 0$ and $\phi = 90$, which means $xz$ and $yz$ planes, respectively. The radiation pattern 3D plot is depicted in Figure 12 with the CDM antenna gain (IEEE) simulated. Observing Figure 12 it is possible to see that in the $yz$ plane the antenna radiation is "donut shaped" and therefore has an omnidirectional radiation pattern for 3.5 GHz.

Figure 12: 3D Radiation pattern plots for 3.5 GHz and 5.8 GHz.

The total efficiency includes the reflection, conduction and dielectric efficiencies whereas the conduction and dielectric efficiencies are usually measured together as the radiation efficiency. For 3.5 GHz, the radiation and total efficiencies have a value of 0.96 and for 5.8 GHz the radiation efficiency is 0.94 and the total efficiency is 0.91. For both 3.5 GHz and 5.8 GHz the efficiencies are considerably good, which means that nearly all power in the input of the antenna is radiated. Note that for 3.5 GHz the radiation and total efficiencies have the same value because the antenna is matched and therefore there are no return losses.

3.3. Antenna Performance Measurements

For the antenna to be manufactured at Instituto de Telecomunicações a mask with a scale 1:1 was
created using QCAD software. The prototype can be seen in Figure 13 alongside with a coin for scale.

Figure 13: CDM antenna prototype with a coin for scale.

The CDM antenna will be the reference element in a SAA, a four element array. More detail on the array design is given in section 4. Therefore, four CDM antenna prototypes were manufactured and numbered from 1 to 4 so they can be distinguished when testing.

The reflection coefficient of each CDM antenna prototype was measured individually, one at a time, and is depicted in Figure 14. Theoretically, the four prototypes should provide the same results as they are identical, and as such the experimental results for the $|S_{11}|$ parameter should be approximately the same.

Figure 14: Measured $|S_{11}|$ parameter of the four CDM antenna prototypes.

Observing the return loss curves it is possible to conclude the CDM antennas number 1, 3 and 4 are practically identical as they provide very similar curves. The antenna number 2 $|S_{11}|$ curve also has the same shape with the exception of having a more accentuated resonance at 5.8 GHz. This could be explained by possible differences in the circuit manufacturing details as there are millimetric gaps between the ground plane and the radiating patch and the feeding strip. Nonetheless, the four CDM antennas are impedance matched as the $|S_{11}|$ is below -10 dB for the whole UWB band.

4. Circular Disk Monopole Antenna Array

After designing the reference CDM element a square shaped structure was chosen for the four element array, as seen in Figure 15. The square shaped structure was preferred in order to take advantage of the CDM antenna’s radiation pattern shape and because of the symmetry achieved.

Figure 15: CDM antenna four element array model.

4.1. Simulation Results

Only port 1 has been excited for the following simulations and the simulations were done with the ports defined as depicted in Figure 16.

Figure 16: Excitation ports.

4.1.1 Reflection Coefficients

The simulated $|S_{11}|$, $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$ parameters are presented in Figure 17. It can be observed that there are two resonances at 5.8 GHz and 9.3 GHz. Although both satisfy the -10 dB condition, only the first is relevant as the ISM 5.8 GHz was chosen as the operating band. Observing Figure 17 it is only possible to see $|S_{21}|$ curves because $|S_{21}| = |S_{41}|$ due to the achieved symmetry in the antenna design.

From Figure 17 it is also possible to see that there is mutual coupling around 9.3 GHz since $|S_{21}| = |S_{41}|$ and $|S_{31}|$ are higher than $|S_{11}|$ and thus meaning low antenna to antenna isolation in that frequency. However, for the desired band the antenna to antenna isolation is good considering $|S_{11}|$ is near -25 dB and $|S_{21}| = |S_{41}|$ and $|S_{31}|$ are near -40 dB.

4.1.2 Radiation Pattern

As previously mentioned, only port 1 is excited as the radiation patterns for the other ports are iden-
Figure 17: Simulated $|S_{11}|$, $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$ parameters of the proposed CDM Antenna Array. Note that $|S_{21}| = |S_{41}|$.

tical.

Figure 18 depicts the radiation pattern polar plot. The radiation pattern plots present the gain (IEEE) in dB for planes $xz$ and $yz$, $\phi = 0$ and $\phi = 90$ in terms of $\theta$, respectively. In the $xz$ plane, when $\phi = 0$, the main lobe direction is 0 and the 3 dB beamwidth is 93.7.

4.1.3 Reflector effect

The reflector was simulated as a Perfect Electric Conductor (PEC) and the purpose of having a reflector with the same shape in the middle of the structure is so that the radiation in the opposite direction each antenna is facing is reflected and consequently a higher gain is achieved in the desired direction. The reflector was placed $\lambda/4$ away from the antennas, where $\lambda$ is the wavelength that corresponds to the center frequency of the band of interest. The ISM 5.8 GHz frequency was chosen for this application and as such the distance between the reflector plane and the antennas is 12.9 mm.

Figure 19 illustrates the effect of the reflector. It is possible to see a higher gain is achieved when using the reflector and at the same time most of the negative $z$ axis radiated power (back lobe) is reflected to the desired direction.

![Figure 19](image)

(a) Array without reflector.  (b) Array with reflector.

Figure 19: CDM Antenna Array radiation pattern polar plots in terms of $\theta$ with $\phi = 0$.

Additionally, the radiation and total efficiencies without the reflector are 0.92 and 0.87, respectively. With the reflector, the radiation and total efficiencies are 0.93 and 0.92 and, as expected, radiation and total efficiencies are lower without the reflector.

4.1.4 Two Ports Excitation

The array can be configured so that two consecutive ports have the signal’s amplitude and phase combined as a way of covering the area in between the two elements. Ports 1 and 2 were excited and Figure 20 depicts the radiation pattern polar plot for planes $xz$ and $yz$, $\phi = 0$ and $\phi = 90$ in terms of $\theta$, respectively. For $\phi = 0$ the main lobe is the 45 direction and the 3 dB beamwidth is 82.2.

4.2. Antenna Performance Measurements

The array prototype was assembled by placing each of the four CDM antennas on the sides of the square structure. The reflector, made of aluminum foil, was inserted inside the notched structure and its dimensions are $34.5 \times 34.5 \text{mm}^2$. The array has a width of 60.3 mm and a height of 38.7 mm. The final prototype of the CDM Antenna Array can be seen in Figure 21.

In an array with four antennas it is possible to analyze the reflection coefficients of each antenna with the remaining ones, which means a total of 16 S-parameters can be studied. The $S_{ii}$ and $S_{ij}$ parameters are presented in Figures 22 and 23, respectively.
5. Conclusions
The main goal of this work was to study solutions and develop an antenna that could be used with a localization system. A low profile and compact solution was developed and further used to build a four element array capable of providing 360° coverage in the azimuth plane.

The solution illustrated in Figure 3 based on SAA and the AoA technique ends up being a very interesting scenario regarding the aim of the work. Additionally, among the studied technologies, UWB is more conducive to better results due to being more tolerant to multi-path effects, which will then result in higher accuracy.

The CDM antenna was designed to operate in the FCC defined UWB band, or at least have an ultra-wide bandwidth of over 500 MHz. A low profile and compact solution was achieved with total height and width dimensions of only 38.7 mm and 37.8 mm, respectively.

When comparing the simulated and measured reflection coefficients of the CDM Antenna, it is observed that the measurements do not show deep resonances at 3.5 GHz and at 9.7 GHz, but instead have a more accentuated resonance at 5.8 GHz. Notwithstanding the mentioned differences, the initially proposed requirements of being compact, low profile and being impedance matched in the UWB band are satisfied experimentally.

Regarding the developed array, a novel design with 4 elements was proposed aiming at making the antenna as compact as possible and still achieve 360° coverage. A square shaped structure was chosen because of its symmetry and a reflector was placed $\lambda/4$ away from the antennas to function as a ground and reflect the backwards radiation in the desired direction, consequently resulting in a gain increase.

The simulated reflection coefficients show a resonance at the band of interest, ISM 5.8 GHz, of -25 dB for the $|S_{11}|$ parameter. A second resonance can be seen at 9.3 GHz, and despite not being in the range of interest, the simulations show there is mutual coupling and therefore the antenna to antenna isolation is low in that frequency.

The CDM Antenna Array was then tested in free space and 16 S-parameters were measured. When comparing the measured $|S_{11}|$ parameter with the obtained in simulations, it shows a slight shift of around 400 MHz of the resonance in the band of interest. Nevertheless, a value of -15 dB is still achieved experimentally at 5.8 GHz, even though the center frequency achieved experimentally is at 5.4 GHz with a value of -26 dB.

As the array was designed in a square shape, this means the antenna can be divided in four 90 sectors and it is possible to conclude that each CDM
element can cover approximately a 90 sector since each antenna has a 3 dB beamwidth of 93.7 in each correspondent direction and two combined antennas can achieve a further gain increase in the sector between them. A possible application for this SAA - CDM Antenna Array, is to perform a scanning beam in an indoor environment. By combining the signal’s amplitude and phase by 50% for each port, the results suggest that an appropriate algorithm could point the main lobe in the desired directions, anticipating the possibility of realizing a scanning array.

Summarizing, the array was designed with a reflector in the center of the structure that resulted in nearly 2 dB increased gain in the desired direction when comparing with no reflector. The total efficiency also improved 5% with the reflector. A SAA with only four elements has been developed to cover a 360° in the azimuth plane, with smaller dimensions than the studied solutions.

References


