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TUTORIAL

Laboratory to Develop a Practical Hand-Made Monopulse Antenna for RFID Localization Systems

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ABSTRACT We describe an educational laboratory to develop a Direction-of-Arrival (DoA) system to locate RFID tags. Along the five proposed sessions, the students will develop the whole system, from the design, manufacturing, and optimization of the antenna to the programming of the location algorithm and testing of a prototype by using commercial RFID tags and a RFID reader. The lab sessions are thought for postgraduate students in Electrical Engineering.

INDEX TERMS Antennas and microwaves, direction-of-arrival, engineering education, postgraduate teaching, RFID, leaky-wave antennas.

I. INTRODUCTION

The teaching of electromagnetics (EM) has been an evolving matter during the years [1], [2], [3], [4], [5]. Previous proposals have been developed so the students take an active role in the learning process. In [2] it is exposed how the students positively value the hands-on labs and simulations while in [3], the manufacturing of hand-made EM devices with common objects shows the feasibility of introducing such teaching labs with reduced budget. In particular, teaching through complete projects has gain lot of interest lately [6], [7], [8], [9], [10] since the students can develop a whole system, which help them to better understand the role that each device plays.

For instance, in [6] the students are proposed to develop the control system of a small radio telescope, under the supervision of the lecturers, from the design and manufacturing of the radio frequency (RF) circuits to the use of different software tools to control the engines of the receiving antenna. The way to implement the project-based learning in EM courses is exposed in [8], [9], and [10].

Such approach has been specifically applied to the teaching of antennas [10], [11], [12], [13], where an active role from the students is key to develop the necessary skills required from an antenna engineer. In this way, the theory is linked to the real-world applications and the different requirements from a specific antenna design, such as radiation pattern, radiation efficiency or bandwidth, can be deeply understood. The requirements can be better understood if the antennas are part of a real system, so that the specifications for the design are set, thus presenting to the students a real-case scenario for the engineering of the antennas. In this sense, monopulse radar systems are of great interest since they combine the antenna design with signal processing. For this reason, different monopulse labs have been presented in the literature [14], [15], [16]. In [14] and [16], commercial antennas are used to develop the monopulse system, which implies a good selection of the proper antenna topology, restricted to the system requirements. However, the process of designing and

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TABLE 1. Lab sessions and objectives.

Objectives	Materials	Lab hours	Hours at home
SESSION I. Introduction to the system and specifications			
• *Establish the scheme and requirements of the system.* The students will acquire the ability to understand the system that is being proposed and set the main specifications for its development.	Pencil, notebook, computer.	2 h	1 h
SESSION II. Design, manufacturing, and test of the antenna. Analogical measurements			
• *Design and manufacture the PLWA.* The students will manufacture an antenna prototype, following a given set of requirements, thus improving their capacity to find the appropriate antenna topology and optimize the design as needed.	Computer with Matlab and ANSYS HFSS, Copper clad FR4 boards, conductive adhesive copper tape, SMA connectors, welding equipment, cutters, rulers, pencils, notebook, vector network analyzer, biconical antenna.	4 h	1 h
• *Test the antenna in anechoic chamber and adjust the designs if needed.* The students will learn how to use the required instrumentation for antenna measurements and the test environment.		4 h	1 h
SESSION III. System integration with programed RFID reader. Digital measurements			
• *Connect and program the commercial devices that form the final system.* Students will understand how the different commercial devices are connected and communicate with each other. • *Measurement of digital radiation patterns.* The students will learn the differences between the analogical and the digital measurements by obtaining the digital radiation patterns that will be used as reference for the DoA estimation algorithm.	RFID reader, router, computer with Eclipse and Matlab, antenna, passive RFID tag.	6 h	1 h
SESSION IV. Signal processing for DoA estimation			
• *Program the algorithms in Matlab for the DoA estimation.* In this session, the students signal processing skills are developed.	Computer with Eclipse and Matlab.	3 h	2 h
SESION V. Experimental Setup and Test in Outdoors Scenario			
• *Test the system with tags in outdoor scenario.* Students will learn to analyze and evaluate the results to show the strengths and weaknesses of the proposed system.	Computer with Eclipse and Matlab software. RFID reader, router, computer, antenna, two RFID passive tags.	4 h	1 h
	TOTAL HOURS	**30 h**	

manufacturing the antenna is not performed. For example, in [15] a planar Yagi dipole antenna for the monopulse system is designed. With such process, the students can also learn about manufacturing techniques.

Recently, monopulse systems have been proposed by using planar antennas [17], [18],[19], [20]. Such type of antennas is very interesting, since they can be easily fabricated with low-cost materials with the instrumentation that is usually available at university facilities. More concretely, Planar Leaky-Wave Antennas (PLWA) have attracted much interest as the receiving element of Direction-of-Arrival (DoA) estimation systems [19], [20], [21], [22], since they provide a beam scanning mechanism without the need of electronic control circuitry that requires more complex hardware, complicates the design and makes it more expensive.

For this reason, a project based on a location application for RFID tags can be designed as part of an educational course that includes both the antenna design and system integration and programming required for data processing. A previous conference paper of the same authors [23], reported only the design of the hand-made antenna used in this lab. As commented, here the students tune the antenna and integrate it in a complete RFID system, and they demonstrate the capacity to estimate the angular location of real RFID tags. Considering the above, the authors propose a project to develop a RFID positioning system based on DoA estimation techniques with a hand-made PLWA. The proposed project is thought to be carried out by postgraduate students that completed courses on (or equivalent) 'electromagnetic fields', 'microwave engineering' and 'antenna engineering' for the antenna design; 'instrumentation' and 'software engineering' for the interconnection between all the equipment and 'digital signal processing' for the acquisition and processing of the relevant data used by the different algorithms.

The paper is distributed as follows. Section II describes the main objectives of the five proposed lab sessions. In Section III, the system specifications are summarized. With them, Section IV focus on the design, hand-made manufacturing, and analog testing of the PLWA. In Section V, the antenna is integrated with a commercial RFID reader, which is conveniently programmed to acquire digital RFID frames. Section VI describes the monopulse signal processing to estimate the DoA of RFID signals, which is used in Section VII to perform angular localization of real RFID tags. Finally, in Section VIII, the results of a survey among the students are analyzed, as feedback to evaluate the interest of this lab to improve the learning process in practical antenna systems.

II. DESCRIPTION AND OBJECTIVES OF THE PROJECT

Along the project, the students will develop a system to locate passive RFID tags through monopulse DoA estimation. A scheme of the system is illustrated in Fig. 1, it is formed by an antenna connected to a commercial RFID reader and a laptop to perform the DoA estimation. Also, commercial

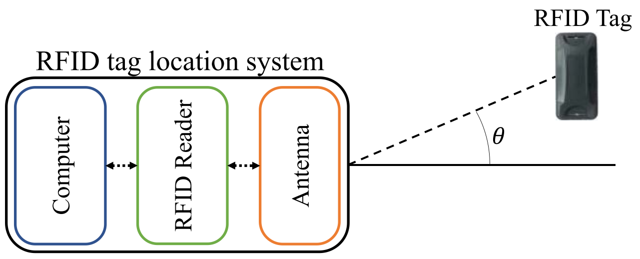

FIGURE 1. Scheme of the proposed RFID tag location system.

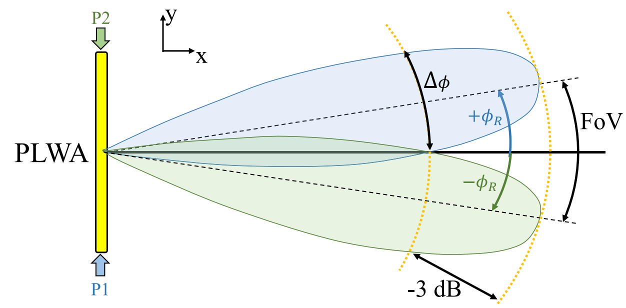

FIGURE 2. Monopulse system based on PLWA overview.

RFID passive tags will be used to demonstrate the capacity of the system to estimate their angular position. Table 1 summarizes the five lab sessions.

Each of the proposed lab sessions will be explained in more detail along the manuscript, specifying the necessary materials and the software provided to the students. As it can be seen, the project duration takes a total of 30 hours, including lab hours and home hours. The home hours are used for the preliminary preparation of the lab session and to prepare a report of the work and results obtained in each session.

This project was included for its development in a module as part of the Master in Telecommunications at Universidad Politécnica de Cartagena, (UPCT) in Spain. In order to evaluate the extent to which the project has been useful for the students, a survey was conducted to receive feedback. The results of the survey are presented in Section VIII of the manuscript.

III. INTRODUCTION TO THE SYSTEM AND SPECIFICATIONS

A. SYSTEM DESCRIPTION

As previously mentioned, the location system is based on amplitude-monopulse processing to estimate the DoA of the backscattered signals coming from a passive RFID tag. To perform such technique, it is necessary to synthesize at least two directive tilted beams that overlap at their half-power (−3 dB) point [24], as depicted in Fig. 2. Bi-directionally fed PLWAs with inherent tilted beams can be used for location purposes, as it has been shown in [25] and applied to different wireless networks, such as Zigbee [26], Bluetooth Low Energy (BLE) [27], WiFi [28] or more recently RFID systems [29]. For that, both ports P1 and P2 of the PLWA are used to synthesize two mirror-symmetric beams, as illustrated in Fig. 2. Thus, it is necessary to use a RFID reader that allows to connect it to external antennas with at least two antenna ports. Obviously, the antenna must be designed to operate in the frequency band of the RFID reader.

To locate the RFID tag, the RFID reader sends a signal and reads the received backscattered signal with a unique tag identifier (tag ID). Also, the reader provides the Received Signal Strength Indicator (RSSI) field to the data package, which is an indicator of the power received by each one of the two antenna ports. The reader sends the tag ID and RSSI data measured at ports P1 and P2 to the PC. Finally, the DoA estimation is performed by comparing the RSSI values obtained through each port, as it is commonly done in amplitude-comparison monopulse systems [27], [29]. Regarding the antenna design, a Half-Width Microstrip (HWM) PLWA is selected [25] to keep a simple topology that can be easily developed and manufactured by the students. This way, the antenna will be hand-made with cheap materials, like FR4 [30], as it will be shown in Section IV.

In summary, there are three elements composing the overall system: 1) PLWA that must be designed and manufactured. 2) RFID reader that must be programmed to send the transmitted signal, read the backscattered frames, and transmit the received data to the computer. 3) Computer running the program that estimates the DoA based on the RSSI data received from two ports of the RFID reader.

B. SPECIFICATIONS

There is a set of parameters that must be specified before developing the system. First, the working frequency band for RFID applications has to be selected. For this project, the UHF 900 MHz frequency band has been selected for two reasons. First, since we need electrically large antennas to synthesize relatively directive beams, it is convenient to use the highest possible frequency, allowing smaller antenna dimensions if compared to lower frequencies [31]. On the other side, if the operating frequencies are too high, the manufacturing tolerances are more critical, and this can compromise the capacity to manufacture the antennas by hand, as it is desired in this project. A trade-off between antenna size and fabrication tolerance can be found in the UHF 900 MHz band. Apart from that, there might be differences between the operating frequencies in different geographical regions. For instance, the RFID UHF band in North America goes from 902 MHz to 928 MHz, while in Europe UHF RFID systems are assigned the frequency range of 865 to 868 MHz. It was found that RFID readers for the North America band give a better flexibility to select the frequency channel to transmit the signal, so for the antenna design, this frequency band will be selected.

With respect to the radiation characteristics of the monopulse system, according to Fig. 2, two beams must be synthetized, pointing to the direction $\pm\phi_R$ and with a certain half power beamwidth $\Delta\phi$. Both parameters are directly

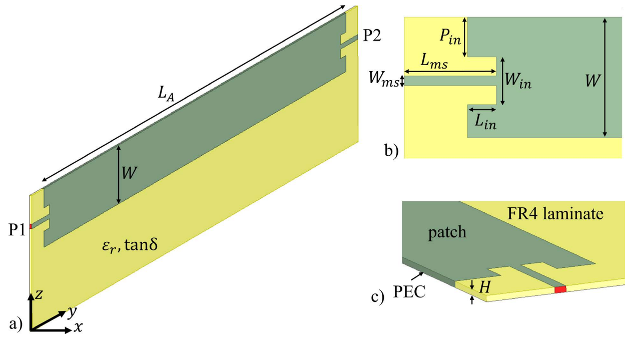

FIGURE 3. HWM LWA topology. a) full antenna, b) feeding network, and c) side view.

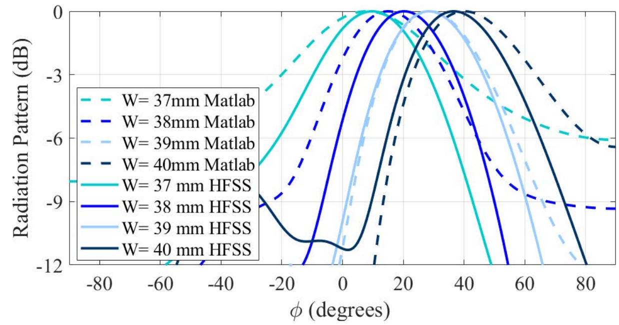

FIGURE 4. Optimization of the strip width W with L = 58 cm.

related to the Field of View (FoV) of the system, that represents the angular range in which the DoA can be estimated without ambiguity [25], [32].

$$\phi_R = \Delta\phi/2 = FoV/2 \tag{1}$$

In order to obtain a wide FoV, broad beams must be synthesized, but this implies a reduction in the system resolution to discern smaller angular changes in the estimation [24]. For a better resolution, the synthesized beams must be narrower. In this case, the chosen FoV is [−20°, +20°], setting the beamwidth to $\Delta\phi = 40°$ and the beam pointing direction to $\phi_R = \pm 20°$ (1). Thus, the system will be able to estimate the DoA of a passive RFID tag that is located in the [−20°, +20°] angular range. During Lab Session I, the monopulse system architecture is studied. As described in Table 1, the students will understand the specifications that determine the scanning angles and half-power widths of the two beams to be generated by the monopulse antenna. These specifications set the requirements, in terms of radiation characteristics, for the antenna that will be designed and hands-on manufactured in Lab Session II, and which is described in the next Section.

IV. DESIGN, MANUFACTURING AND TEST OF THE ANTENNA. ANALOG MEASUREMENTS

In Lab Session II, the theoretical design of the antenna and its optimization is studied. Subsequently, the design is manufactured and tested with analog instrumentation (Vector Network Analyzer or VNA) in the anechoic chamber to obtain its radiation patterns and S parameters. As previously commented, the selected topology is the HWM LWA, which is presented in Fig. 3. It is basically formed by a long radiating microstrip line made with copper, which is grounded in one side also using copper tape. Such topology is chosen for its simplicity and ease of fabrication. As will be shown later, it is only necessary to stick copper tape to a grounded dielectric substrate and cut it with the proper profile.

A. DESIGN AND MANUFACTURING

The main two dimensions of the HWM LWA to be designed are the radiating microstrip width W and length L_A, which are sketched in Fig. 3. The width W determines the desired scanning angle ϕ_R for the operating frequency, and it can be approximated by the next expression [28], [29]:

$$W \approx \frac{\lambda_0}{4} \frac{1}{\sqrt{\varepsilon_r - sin^2\phi_R}} \tag{2}$$

where λ_0 is the wavelength ($\lambda_0 = 33$ cm at $f_0 = 902$ MHz) and $\varepsilon_r = 4.5$ is the dielectric constant of the FR4 substrate [33]. With those values and a desired radiation angle of $\phi_R = 20°$, the obtained width was $W = 39.7$ mm. From (2), it is easy to see that by increasing or decreasing the strip width W, the scanning direction ϕ_R can be theoretically tuned to higher or lower angles, respectively.

For the case of the antenna length L_A, it can be obtained through the known approximation that relates it to the beamwidth $\Delta\phi$ [30], [27]:

$$L_A \approx \lambda_0 \frac{57°}{\Delta\phi} \frac{1}{cos\phi_R} \tag{3}$$

In our design, with $\Delta\phi = 40°$ and $\phi_R = 20°$, the theoretical antenna length is set to $L_A = 50.4$ cm. By increasing or decreasing the antenna length L_A, the radiated beams can be theoretically adjusted to become narrower or wider, respectively.

1) ANTENNA NUMERICAL DESIGN AND OPTIMIZATION IN MATLAB AND ANSYS HFSS

Once the main dimensions of the radiating strip, W and L_A have been theoretically calculated by using the approximated expressions (2) and (3), the HWM LWA must be optimized before manufacturing. For that, firstly the antenna is analyzed and designed with an in-house tool programmed in Matlab, based on a transversal resonance method [34], [35], to consider the losses and thickness of the laminate ($\tan\delta = 0.018$ and $H = 1.6$ mm). Subsequently, more precise full-wave simulations will be carried out with the commercial software Ansys HFSS to verify the results and to optimize the feeding network (Fig. 3b) in order to keep a good matching (parameter S_{11} below −10 dB) at the operating frequencies.

In the provided Matlab graphical user interface, W and L_A must be simultaneously optimized to adjust the radiation pattern (scan direction ϕ_R and beamwidth $\Delta\phi$) as desired. Since the antenna will be manufactured by hand, the width W and length L_A will be varied in 1 mm steps due to the low manufacturing tolerances that can be manually achieved.

TABLE 2. Theoretical, numerical and experimental design values.

	Theoretical	Numerical (Matlab)	Numerical (HFSS)	Exp 1	Exp. 2 (tuned)
W (mm)	39.7 (2)	38	38	38	37
L (cm)	50.4 (3)	58	58	58	58
ϕ_R (°)	20 (1)	15	22	30	21
$\Delta\phi$ (°)	40 (1)	36.5	39.5	59	43

TABLE 3. Dimensions of the feeding network.

Dimension	Value (mm)
W_{ms}	3
W_{in}	15
L_{in}	9
L_{ms}	29
P_{in}	11.5

As an example of this tuning process, Fig. 4 shows the radiation patterns obtained when W is varied from 37 mm to 40 mm in the aforementioned 1 mm steps. As observed in Fig. 4 with dotted lines, the Matlab tool predicts an increase of around 10° in the scanning direction as W is varied 1 mm, showing that $\phi_R = 8°$ with $W = 37$ mm while $\phi_R = 39°$ with $W = 40$ mm. Therefore, the optimal design obtained with the Matlab tool is found to be $W = 38$ mm, which provides a scanning angle of $\phi_R = 15°$ and a suitable half-power beam width which intersects the perpendicular direction $\phi_R = 0°$ at its -3 dB gain drop point.

The length of the antenna had to be also adjusted since at lower radiation angles and due to losses in the substrate, the beamwidth broadens [30]. Then, the antenna length was set to $L_A = 58$ cm, synthesizing a beamwidth of $\Delta\phi = 36.5°$. To validate the results, the design is simulated in HFSS with a model provided to the students, obtaining a pointing angle of $\phi_R = 22°$ and a beamwidth of $\Delta\phi = 39.5°$, which is very close to the desired requirements, as can be seen in Table 2. The next step is to optimize the dimensions of the feeding network shown in Fig. 3b. At this stage, the Ansys HFSS optimization tool is used to obtain the appropriate values to reduce reflections from the ports. The optimized dimensions of the feeding network are presented in Table 3. With those dimensions, the optimized structure is simulated to assess the proper performance with good matching and the correct radiation pattern. The S parameters are depicted in Fig. 5, showing a good matching with S_{11} below -10 dB at the design frequency of 902 MHz. The parameter S_{21} below -10 dB, which measures the coupling between ports, indicates a radiation efficiency above 90%. As commented, full-wave HFSS simulations are necessary for the accurate analysis and optimization of the antenna including the input matching circuits before manufacturing. However, the initial design values provided by the Matlab code allows the optimization to be tackled in a more time-efficient way. The optimization with ad-hoc Matlab tool takes only about 5 minutes, while in HFSS it can take several hours.

Also, it is important to note that as demonstrated with both Matlab and HFSS simulations in Fig. 4, fabrication tolerances of the metallic strip width of only 1 mm imply a change in the pointing angle of the antenna of around 10°. Therefore, it is important to be precise when fabricating the homemade antenna to obtain the desired scanning angle. The manufacturing process is described below.

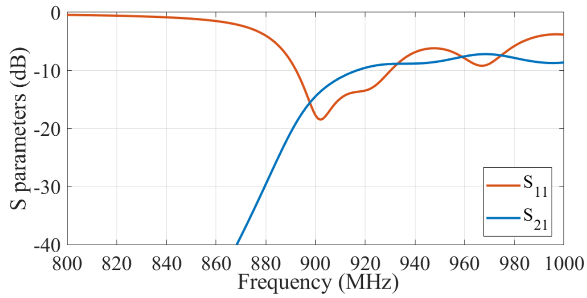

FIGURE 5. Antenna S parameters simulated in HFSS.

2) DO-IT-YOURSELF: FABRICATION OF THE HWM LWA

For the manufacturing of the HWM LWA, a low-cost FR4 board was acquired [33]. It is grounded with a copper layer at one side, so the radiating strip will be added at the other side of the board. The dimensions of the board are 91.4 × 60.9 cm, which allows to manufacture several antennas along the shorter dimension of the board. To create the radiating strip and the feeding network, copper tape [36] is used. The copper tape length is 16 m, and the width is 50 mm, sufficient to construct the radiating strip with $W = 38$ mm and $L_A = 58$ cm. It is important to note that the width W must remain constant throughout the 58 cm length of the LWA. Therefore, a long ruler is requested to avoid width variations while cutting the copper tape with a cutter.

With all these materials, the next fabrication steps can be followed as illustrated in Fig. 6. The first step is to stick the copper tape, from the edge of the board to the design width $W = 38$ mm, as seen in Fig. 6a. To create the Perfect Electrical Conductor (PEC) wall on the grounded side of the microstrip LWA, the copper tape is wrapped around the edge of the FR4 board and sticked to the ground, as shown in Fig. 6b. Then, the feeding network is drawn, and the excess tape is removed with the help of a cutter, see Fig. 6c. After that, the SMA connectors are welded to the microstrip lines and the ground plane, as shown in Fig. 6d. The final step is to cut the FR4 board to separate the fabricated antenna from the rest of the board, as shown in Fig. 6e. This final step can also be done before the manufacturing process. Finally, the manufactured antenna is presented in Fig. 6f. An aluminum ground plane with dimensions of 59.5 × 30 cm is used to avoid back radiation from the antenna and increase the gain in the front side. As summarized in Table 1, the first half of Lab Session II is dedicated to the computer-aided design of the antenna and hand-made manufacturing.

B. TESTING AND FINE-TUNING: ANALOGICAL EXPERIMENTS OBTAINED IN ANECHOIC CHAMBER

To validate the proper performance of the antenna, the radiation pattern must be measured and compared with the

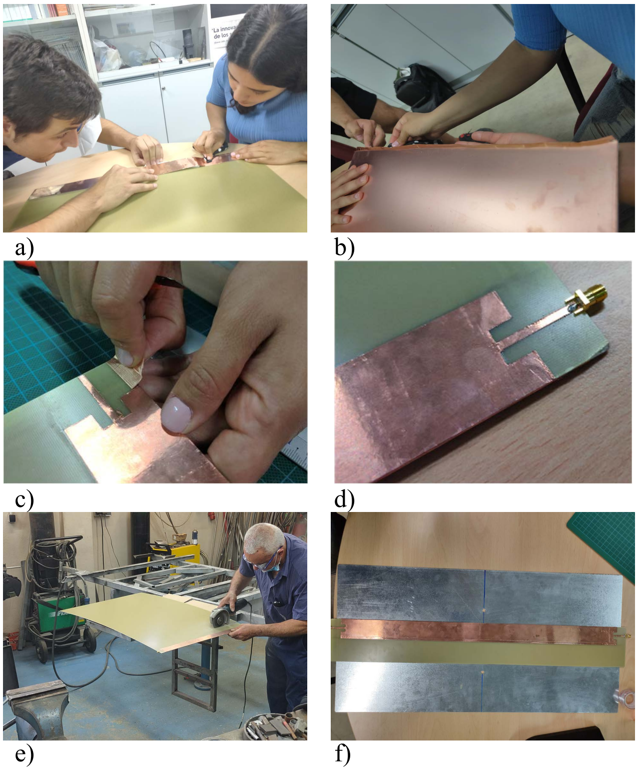

FIGURE 6. **HWM LWA manufacturing process. a) Stick the copper tape to the FR4 clad board, b) Creation of PEC wall by wrapping around the copper tape, c) Cutting and removing copper tape to create feeding network. d) Welded SMA connector, e) Cutting the FR4 board, and f) Final prototype.**

theoretical one. This is done in an anechoic chamber with the help of a VNA. The setup is shown in Fig. 7a, where port 1 of the LWA is connected to port 1 of the VNA while a reference antenna is connected to port 2 of the VNA. Port 2 of the LWA will be connected to a matched load in order to avoid the remaining non-radiated power to reflect and re-radiate. The students are provided the necessary software to obtain the measurements of the S_{21} parameter from the VNA at the same time the turn table is rotated from $-90°$ to $+90°$. Depending on the used VNA, the commands to read the data may be different.

Finally, the obtained radiation pattern is shown in Fig. 7b in blue dashed line. As observed, the radiation angle is shifted with respect to the simulated one (Fig. 7b in black line), pointing at $\phi_R = 30°$ instead of the desired $\phi_R = 20°$. Since we are using the low-cost FR4 material to manufacture the antennas, the tolerance dielectric constant ε_r of the received board might be in the range from 4.2 to 4.8, depending on the manufacturer and due to the high tolerances. For this, it is not possible to know a priori the real value of ε_r, so a difference between the value of the real FR4 board and the one used in simulations may lead to the shifting of the pointing angle due to the dispersive nature of LWAs, as it has been observed with the measurement.

To correct the prototype, as it was shown in Fig. 4, the width of the radiating strip must be changed. Cutting the strip will reduce the radiating angle, while adding copper tape to

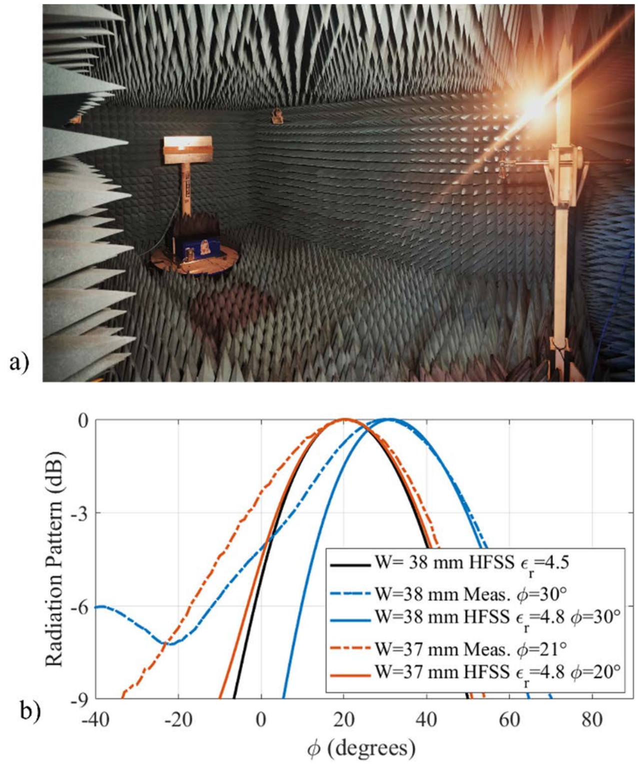

FIGURE 7. **Measurement of analogical radiation patterns. a) Setup in anechoic chamber, and b) Tuning of the radiation patterns by adjusting strip width W.**

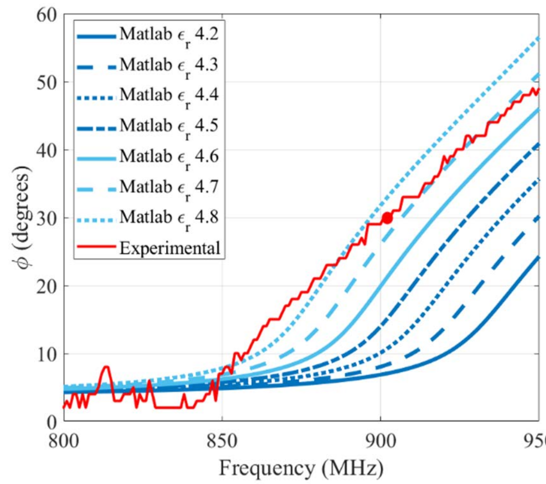

FIGURE 8. **Dispersion varying ε_r for W = 38 mm. Real value estimated of $\varepsilon_r = 4.8$.**

make it wider will lead to a higher radiation angle. Previously, it is important to evaluate the real ε_r. For that, simulations on the dispersion of the LWA (the change of the pointing angle with the frequency), are performed for a range of values of ε_r from 4.2 to 4.8 and with $W = 38$ mm, as depicted in Fig. 8. The measured dispersion is compared with the simulations to estimate the value of ε_r. As demonstrated in Fig. 8 in the UHF RFID frequency band, the value that best fits measurements is $\varepsilon_r = 4.8$. As can be seen in Fig. 7b, this adjusted value of

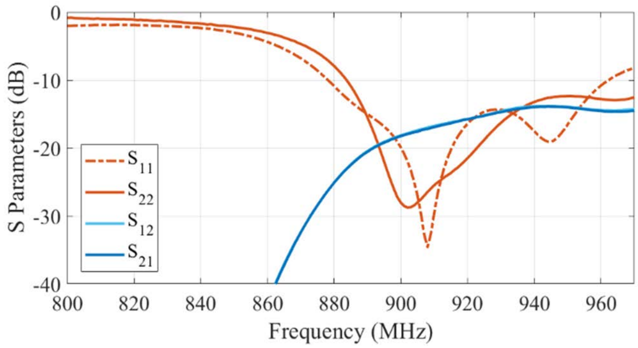

FIGURE 9. Measured parameters.

$\varepsilon_r = 4.8$ predicts the shift in the measured radiation pattern direction towards $\phi = 30°$ with $W = 38$ mm. Therefore, the strip width W must be tuned to obtain the desired scanning direction of $\phi = 20°$. As expected, the optimum width must be reduced in the order of 1 mm to $W = 37$ mm to reduce the scanning direction from $\phi = 30°$ to $\phi = 20°$. Thus, 1 mm must be removed from the radiating strip with a cutter, as it was done to create the feeding network, resulting in the final prototype. The radiation pattern is measured for the corrected antenna, presenting a peak at the desired angle $\phi = 21°$ as demonstrated in Fig. 7b. Finally, the measured S parameters of the adjusted antenna, in Fig. 9, indicate a good matching and isolation below -10 dB in the whole frequency band from 902 MHz to 928 MHz, as predicted by simulations in Fig. 5. The testing and tuning of the antenna described in this Section are the main tasks performed in the last half of Lab Session II.

V. SYSTEM INTEGRATION WITH PROGRAMED RFID READER. DIGITAL MEASUREMENTS

Once the antenna is manufactured and tuned, the integration of all the devices of the system is done in Lab Session III. The scheme of the devices' interconnection is depicted in Fig. 10. We have chosen the commercial UHF RFID reader Impinj Speedway R-420, which operates in the frequency range from 860 to 960 MHz and offers four antenna ports [37]. Both ports of the HWM LWA are connected to two ports of the RFID reader with coaxial cables. The RFID reader [37] is controlled by a PC via Ethernet connection using a router. The TCP/IP communication with the reader is software controlled through Eclipse. The controller of the reader allows to acquire RFID frames that contain in the header the tag ID the RSSI level and the used frequency channel. In this way, the RFID signals are captured and post-processed in Matlab. In order to implement this, both software entities must be synchronized with the measurement system.

When all the different programs are synchronized, the digital radiation patterns can be measured. To do so, the experimental setup is shown in Fig. 11, where the antenna and the RFID reader are placed inside the anechoic chamber on a rotating table, which is also controlled with an additional Matlab script. The commercial RFID passive tag Omni-ID

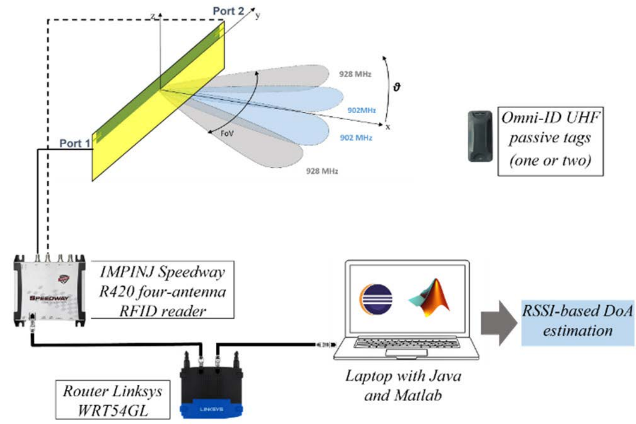

FIGURE 10. Experimental set-up and system integration.

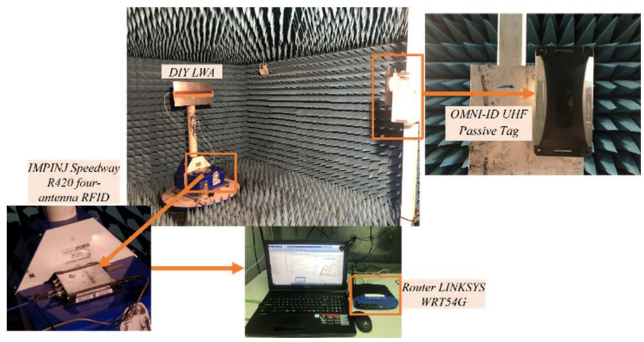

FIGURE 11. Experimental set-up in anechoic chamber.

Dura 3000 [39] is placed at 2.5 m from the HWM LWA to backscatter the signal. This commercial tag can operate at a distance of to 35 m and it is designed for outdoor UHF applications such as the one presented in this paper.

Once the scenario is set up, the radiation patterns are measured by rotating the table from $-90°$ to $+90°$ with a resolution of one degree. Therefore, the reader performs 100 detections from both antenna ports at every integer angle. Once the aforementioned information is processed, an averaged RSSI from all the single detections is obtained for every position of the table, conforming the radiation patterns presented in Fig. 12, which are normalized with respect to their maximum value. The digital patterns for other RFID channels are equally obtained by reconfiguring the transmitting frequency of the reader. If more channels are included in the algorithm, it is possible to reduce the ambiguity of the DoA estimation, as demonstrated in [29]. Fig. 12 depicts the measured digital radiation patterns at three different frequencies in the RFID American band: 902 MHz, 914 MHz and 928 MHz, although all the 50 available channels in this band can be used. At the lower frequency of 902 MHz, the patterns are pointing to 20°, with an overlapping point at their -3 dB levels at 0°. For the highest frequency of 928 MHz, the beams are scanned towards higher angles, so the overlapping point happens at a lower level (-6 dB). This dispersive behaviour, typical from LWAs, is well known as frequency beam squinting. The study presented in [29] proves that

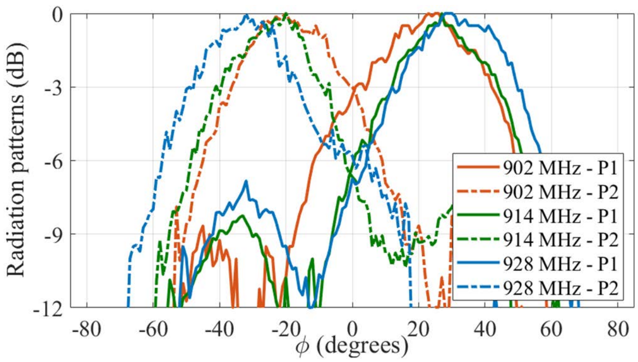

FIGURE 12. Digital normalized radiation patterns.

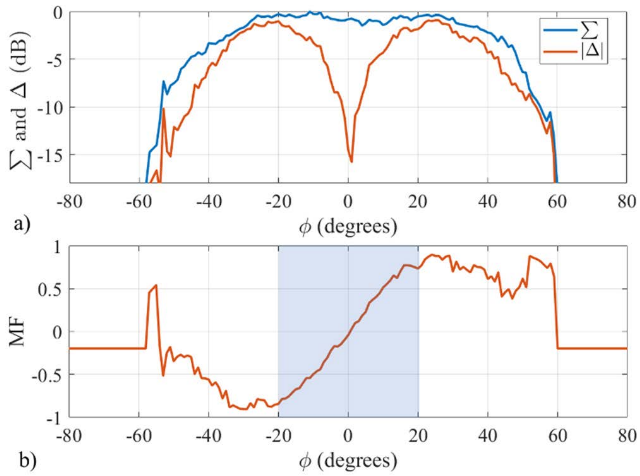

FIGURE 13. Digital patterns at 902 MHz. a) $\sum$ and Δ patterns, and b) Monopulse Function.

it can be used to eliminate ambiguities by using different Monopulse Functions (MFs) at different frequencies. The measured patterns will set the reference power level to be included in our DoA estimation algorithm, which will be programmed and tested in Lab Session IV.

VI. SIGNAL PROCESSING FOR DoA ESTIMATION

Next steps consist of programming and testing the DoA estimation algorithm. For that, all the data obtained in the digital measurements are now loaded into Matlab, where it is processed to obtain the reference MF as combination of the sum and difference patterns [19]:

$$MF(\phi) = \frac{\Delta(\phi)}{\sum(\phi)} = \frac{RP_1(\phi) - RP_2(\phi)}{RP_1(\phi) + RP_2(\phi)} \quad (4)$$

where $RP_1(\phi)$ and $RP_2(\phi)$ correspond to the previously obtained normalized digital radiation patterns from antenna ports 1 and 2 of the RFID reader, respectively. The FoV is defined as the angular range where the MF linearly increases [32]. In this range, each monopulse value (which can vary from -1 to 1) is uniquely related to an angle.

The obtained digital sum and difference patterns for lowest channel at 902 MHz is illustrated in Fig. 13a, and the corresponding MF is shown in Fig. 13b. The obtained FoV, marked in Fig. 13b in blue shadow, is around $[-20°, +20°]$, which is consistent with the requirements defined in Lab Session 1. To reduce ambiguity in amplitude-monopulse systems with LWAs (so that a signal coming from outside the FoV does not create a false estimation inside the FoV [32]), MFs at different frequencies can be used [29]. Such MFs are derived from patterns scanned at different angles, creating the necessary diversity to eliminate the ambiguity. This is shown in Fig. 14, where the MFs at different frequencies are presented (Fig. 14a). Each MF presents slightly different FoV and form. Then, the DoA estimation from a backscattered signal can be computed by obtaining a Monopulse Value (MV) with the received RSSI from both ports and comparing it to its corresponding reference MF (at the same frequency):

$$MV = \frac{RSSI_{P1} - RSSI_{P2}}{RSSI_{P1} + RSSI_{P2}} \quad (5)$$

From that comparison, an angular pseudospectrum (APS) is obtained, with a peak at the estimated DoA [19]:

$$APS = 10log\left(\frac{1}{EF(\phi)}\right) \quad (6)$$

$$EF(\phi) = |MF(\phi) - MV| \quad (7)$$

where EF is the error function from the comparison between the MV and the corresponding MF. This is depicted in Fig. 14b for a signal coming from $\phi = 10°$. As observed, there are many other peaks apart from the one of the real direction, when a single MF is used. By using different MF from different frequency channels, the ambiguity can be reduced, obtaining a single peak with the final DoA estimation [29]. Thus, in order to perform a DoA estimation, the reader must send the following information to the computer running the algorithm: RSSI, associated antenna port, RFID tag ID and frequency channel.

Once the information from both ports and all used frequencies has been received, the DoA estimation can be computed. To combine the information from the different MFs at different channels, the EF in (7) must be substituted by the Overall Cumulative Error (OCE) from which a combined APS (CAPS) is obtained:

$$OCE(\phi) = \sqrt{\sum_{m=1}^{M} \frac{1}{M} EF_m(\phi)^2} \quad (8)$$

$$CAPS = 10log\left(1/OCE(\phi)\right) \quad (9)$$

with m representing each MF at different frequencies and M the total number of used MFs. The CAPS obtained from the combination of three different RFID channels is shown in yellow in Fig. 14b. As can be seen, the multiple peaks in the APS obtained for each single channel, are reduced to one unique peak corresponding to the common DoA, which is the real one once ambiguity have been removed. This process can be performed for multiple tags simultaneously,

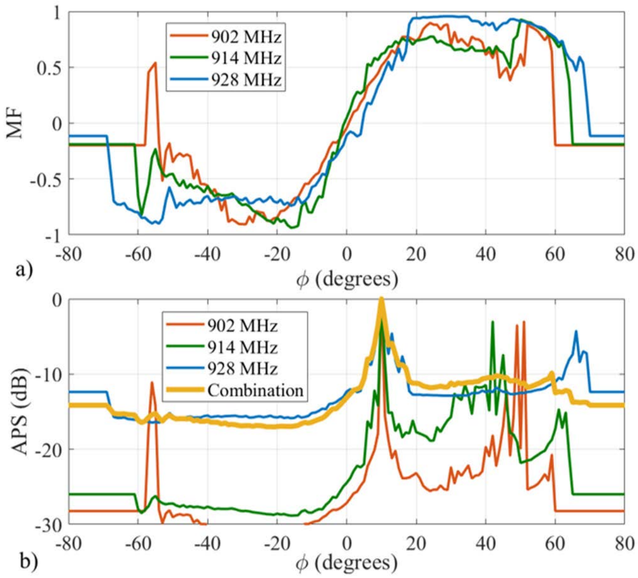

FIGURE 14. DoA estimation for $\phi = 10$o. a) MF at different frequencies, and b) APS with single MF and with all combined.

TABLE 4. Expected and measured angles.

Expected angle (°)	Measured angle (°)
-15	-18.2
-10	-10.8
- 5	-5
5	4.3
10	9.6
15	12.3

since the RFID tag ID is included in the information received by the RFID reader. The algorithm will be explained to the students in Lab. Session IV, so that they will be able to program it in Matlab, together with the data acquisition routines.

VII. EXPERIMENTAL SET-UP AND TEST IN OUTDOOR SCENARIO

In the last Lab Session V, the developed RFID monopulse system is put to test in a realistic outdoor scenario. For that, the antenna, RFID reader and router are mounted on a mast in a fixed position and different RFID tags are mounted on different masts that will be moved at different positions, as illustrated in Fig. 15. The laptop will be running the program in Eclipse that receives the data from the RFID reader and sends it to the script running the DoA estimation algorithm in Matlab.

For this case, the program in Matlab will receive only 4 RSSI samples per each port and frequency (instead of the 100 samples used in the calibration process) to perform a quicker DoA estimation. As it was done to obtain the digital radiation patterns, these samples will be averaged and compared to the reference monopulse functions that were obtained in Lab Session IV. At this stage, the system can

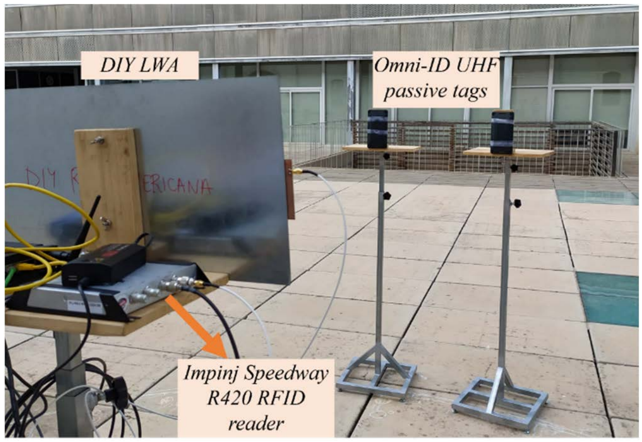

FIGURE 15. Digital patterns at 902 MHz. a) $\sum$ and Δ patterns, and b) Monopulse Function.

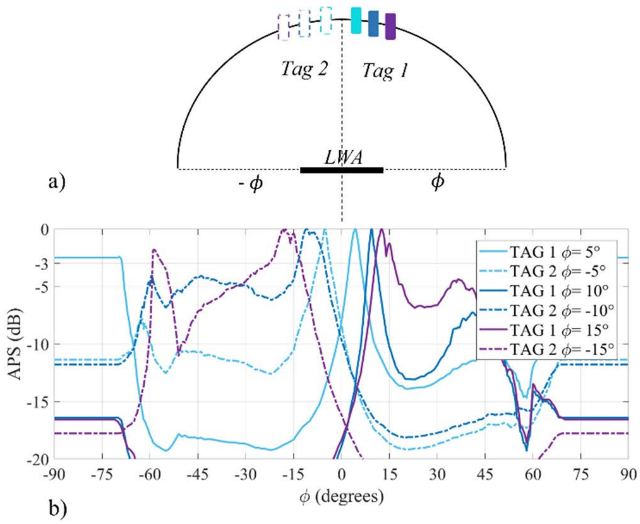

FIGURE 16. Angular Pseudospectrum for the three channels employes, and differents tag position.

distinguish between different RFID tags, since their unique ID is encoded in the backscattered signal, so the location can be performed for more than one tag at the same time. The RFID tags are located at the same distance of 2.5 m which was used to calibrate the antenna monopulse functions. It must be taken into account that, for the operating frequency (900 MHz) and antenna maximum size (L_A= 58 cm), the far-field distance is 2 m. Therefore, the near-field effects should be considered for precise DoA estimation at distances below 2 m, as explained in [40]. This could be done by re-calibrating the digital monopulse functions for different distances in close proximity of the antenna.

With this set-up, the DoA of the two RFID tags will be estimated for three different angles each. Tag 1 at positive angles and Tag 2 at negative angles, as illustrated in the top scheme of Fig. 16a. The tags are moved to different angles from $\phi = \pm 5°$ to $\phi = \pm 15°$ and in each position, the DoA is estimated. This can be observed in Fig. 16b, which shows the different APS for each measurement. Table 4 shows

TABLE 5. Learning outcomes from the realization of the proposed project.

Student survey (abilities)	Average
1. Understanding and applying monopulse LWA design theoretical concepts.	4.0
2. Using HFSS software for simulation and optimization of the proposed LWA.	4.0
3. Hand-made fabrication and fine-tuning of a real LWA.	4.5
4. Analogical and digital calibration of the LWA in the anechoic chamber.	4.0
5. Connecting and communicating instruments needed for the RFID direction-finding systems (antenna, reader, tags, CPU computer).	3.8
6. Acquisition and processing of UHF signals and programming the DoA estimation with Matlab.	4.2
7. Digital testing of the RFID system in outdoor scenario using passive RFID tags.	3.9
8. Understanding the overall design process and interdependence between the parts of this radio direction-finding project (antenna EM design, programming of Digital Signal Processing and final application).	4.8

the measured and expected angles to compare the angular position.

In this last Lab. Session V, the students record the obtained APS for each angular position and write the estimated DoA from the peaks of the APS. The plot of the APS in Fig. 16b and the DoA estimations are obtained with a latency of 4 seconds, so the students can check in real time the accuracy of the RFID localization system as they move the tags to different position.

VIII. LEARNING, OUTCOMES, SURVEY AND DELIVERABLES

Since the project is included as part of a Master program in Telecommunications Engineering or similar, it is intended to reinforce a set of skills for the future antenna engineer. For this purpose, a satisfaction survey was conducted with 15 postgraduate students within the Telecommunications Engineering program. The survey was conducted with a total of 8 questions. The students answered the survey anonymously, on the day of the last session without the presence of the teacher, so that they felt free to answer each question. According to the degree to which the student considers that their knowledge and skills have improved, they have to score on a scale from 0.0 to 5.0 each survey item (where 0.0 is the lowest rating and 5.0 is the highest). The mean results and learning outcomes are presented in Table 5.

As observed in the survey, the highest score was 4.8, where students learned how to design and manufacture an antenna for RFID applications. Certainly, this project can help to understand the interdependence of all the parts involved (antenna, hardware, communication software, signal processing), and the necessity to take them all into account for a proper design. On the other hand, the lowest score was 3.8, given to the connection and synchronization of the hardware, since to establish the communications between devices (reader-Matlab) an intermediate level of programming with Java and Matlab was required. However, most of the overall scores are above 4.0.

In addition, with the results obtained from the surveys, we were able to distinguish two different student profiles. Some of the students preferred computer-aided design and signal programming, while others valued more their skills in manufacturing, assembling and testing the antenna system in different scenarios.

IX. CONCLUSION

We have proposed a laboratory to develop a practical RFID monopulse localization system. It is divided in five lab sessions. In the first session students can understand the specifications of an amplitude monopulse antenna to cover a certain angular field-of-view by creating two directive tilted beams which overlap in the perpendicular direction. Then, these specifications are translated into a real design of a simple microstrip monopulse leaky-wave antenna, which is fabricated by themselves using low-cost materials and manual processes in the second session. Also in this second session, the manufactured antenna prototype is tested in an anechoic chamber, and students learn how to manually tune the scanning direction by just adjusting the microstrip width. Communication skills between a real RFID reader and a personal computer are developed on the third session, where they program a commercial RFID reader to acquire frames and obtain important data, such as the tag ID, the used frequency, and the RSSI values. In addition, in this session they learn how to obtain the digital radiation pattern of the monopulse antenna connected to the RFID. In Session IV, basic amplitude comparison principles are put into practice by programming the signal processing to estimate the Direction-of-Arrival from the measured RSSI. Finally, they test the performance of the developed RFID localization system, simultaneously estimating the angular location of two tags in real time.

As a future work, it can be noticed that the designed antenna has a limited angular Field of View (FoV) of only 40°. As explained in [29] and [41], this FoV can be extended by using a substrate with higher dielectric permittivity (for instance using $\varepsilon_r = 10$ as in [28], [29], and [41]). This makes the LWA more dispersive with frequency, and the resulting frequency-beam squinting can be used as a positive frequency beam scanning mechanism to create several monopulse functions covering different angular regions. In this way, the FoV can be increased up to 120° as demonstrated in [41]. Another future work involves the extension from 1D to 2D angular localization, by using two LWAs in cross-shaped topology as proposed in [42].

We believe that the proposed laboratory initiative can help the student to gain a more interdisciplinary vision of the antenna engineer world, which requires an interdependent design that includes electromagnetism, digital hardware communications, and signal processing programming. From the feedback of the students, this important challenge is provided with this practical educational initiative. Annex I summarizes the resources available for the students, which are available in IEEE Antennas and Propagation Society (APS) Resource

Center. Finally, Annex II summarizes the materials requested to develop this lab, together with the estimated cost of each material item.

ANNEX I RESOURCES AVAILABLE FOR THE STUDENTS

The following resources for the students are available at IEEE APS Resource Center, see [43]:

1) PDF files with detailed instructions to buy the requested materials, design and fabricate the LWA.
2) Program in Matlab for design LWA.
3) Eclipse Codes in Matlab.
4) PDF file. User's Guide Analytical Design in Matlab of DIY LWA.
5) PDF file. User's Guide Commercial Reader Impinj R420.
6) Video to guide the student along the project realization.
7) PDF survey.

ANNEX II LIST OF MATERIALS

The following table summarizes the cost of the materials associated to this lab (the anechoic chamber and associated instrumentation is not included):

Materials		Units	Unit price (euros)
	Copper Clad Boards, 1.6 mm thickness, single sided 91 x 60 cm. 1/16in., [33]	1	86,17 €
	Conductive Adhesive copper tape, 50.8 mm x 16 m [36]	1	151,46 €
	Coaxial conector [38]	2	2,58 €
	Cutter, ruler, pencils	1	18,0 €
	IMPINJ Speedway R420 four-antenna RFID reader [37]	1	1500 €
	PC	1	599 €
	Omni-ID Dura 3000 RFID Passive Tag [39]	5	24 €
	Linksys WRT54GL Router [44]	1	29,90 €
	Ethernet cables	4	9 €
TOTAL PRICE			2420,11 €

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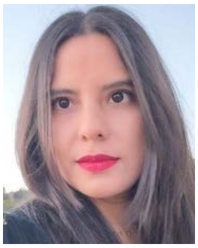

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