Abstract—Wearable devices, as well as their related applications and services, are more and more important in the steady increase of the global IP traffic. They are now an important part of the Internet of Things (IoT)/Internet of Everything (IoE).

The proposed structure is a dual-band antenna with two metal layers for use in security, health/medical care, and personnel tracking applications. This dissertation proposes an antenna of 82.6 x 20 x 3.5 mm\(^3\) with three parallel rectangular slots of 46.5 x 1.5 mm\(^2\), equispaced of 1 mm, placed in ground plane and near the lowest band port. Its prototype was built and tested. The antenna operates in the Wireless-Fidelity (Wi-Fi) and Bluetooth (BT) bands, in the 2.45 GHz Industrial, Scientific and Medical (ISM) band, and in Global Positioning System (GPS)/GLONASS/Galileo L1 bands.

In two distinct stages, Scattering-parameters (S-parameters), bandwidths, feeding, radiating patterns and radiating efficiency were analysed. First in free-space, due to isolation issues, it became necessary to approach decoupling techniques. In a second stage, the antenna was studied when folded and integrated in an ankle bracelet, inspired by a commercial application, and then when placed close to an ankle and foot model. The Specific Absorption Rate (SAR) was also evaluated.

Regarding the results of the first stage, there was a satisfactory agreement between the simulation and the experimental S-parameters results in the bands of interest, which validates the procedure used. The second stage led to promising simulation results for a proof of concept.

Index Terms—Ankle bracelet antenna, Dual-band antenna, GPS, BT, Wi-Fi

I. INTRODUCTION

Mobility or portability has been equated with wearability, where a set of communication and sensor components, integrated into wearable devices or attached to the human body, provides freedom and utility for people in their day-to-day tasks. Therefore, these antennas specifically designed to work while being worn, known as wearable antennas, are a technology trend of the utmost interest and increasingly common in the current consumer electronics. In this sense, the concept of Wireless Body Area Network (WBAN) is more often present in today’s wireless networks [1].

When compared with other types of antennas, wearable antennas design faces off unique difficulties in respect of miniaturisation and close proximity to the human body. Most bracelet-wearables are not completely standalone devices, because they lack an Internet connection. Hence, many of the bracelet-wearable devices are designed to connect, mostly via Bluetooth (BT), with other devices that do have Internet connectivity, namely smartphones, tablets or computers [2].

Wearable antennas have been used in different types of communications inside WBANs: on-body (as shown in [3]), off-body [4] and in-body [5] [6].

The design procedure of wearable antennas comprises different steps, varying from choice of material to antenna measurements. Through the last years, there are different conductors and dielectrics, from the traditional materials to the more and more trendy and forward-looking ones, that have been commonly utilised. Conductors have been used such as pure metals [7], [8], [9]; conductive inks [10]; more recently conductive graphene layers [11] and conductive sprays [12]. There are dielectrics such as soft PCB substrate based on films (polyimide films [13], [14]; polyethylene terephthalate films [15], [16]; and liquid crystal polymer films [17], [18], [19]); paper substrate [20], [21] [22]; polydimethylsiloxane [23], [24], [25]; and foams [26], [27]. Moreover, different fabrication techniques have been applied over time such as line patterning, screen printing, thermal evaporation, ink-jet printing, and more recently, 3D Printing/Additive Manufacturing.

In this work, a dual-band antenna with two metal layers is designed and developed for possible use in security, health/medical care, and personnel tracking applications. To that end, the antenna is integrated into a commercial ankle bracelet-wearable device. Moreover, the antenna should work in the presence of human body and, therefore, its radiation patterns should be directed off-body and above the level of the ankle.

This antenna has been conceived to operate in the 2.4 GHz ISM Band and in the upper Navigation Services L1 bands, in the context of off-body communication systems. Within the 2.4 GHz ISM Band, it is intended to cover the BT band (2400 - 2483.5 MHz, including guard bands 2 MHz wide at the bottom end, and 3.5 MHz wide at the top) and Wi-Fi 802.11 (2401 - 2495 MHz); the upper L1 bands include GPS L1 (1563 - 1587 MHz), Galileo E1 (1559 - 1591 MHz) and GLONASS G1 (1593 - 1610 MHz). In this document, the antenna design and performance are studied in two different stages: (1) in free-space condition and (2) in non-free-space conditions. Considering the most common criterion in antenna design, the S-parameters should be below -10 dB for both the reflection and transmission losses, in the bands of interest.

In Section II, a parametric study is carried out to understand how each antenna parameter and feed line and positioning may affect the overall antenna performance, which includes reflection and transmission coefficients (S-parameters), operating bands, and radiation patterns and efficiency. Different ways of approaching to enhance the isolation/decoupling for dual or multi-port antennas are discussed in order to mitigate undesired coupling effects. In this project, the use of slots is taken into account as possible defected ground structure, for
purposes of simulation and test. Even an analysis of the surface current distribution on the antenna ground plane was done. A prototype was built by using Kapton® as conductor material, through a photolithography process as fabrication technique, and then is tested. Regarding the second step, in Section III, series of simulations is done to study the antenna behaviour under non-free conditions, such as bending, casing into an ankle bracelet model and in close proximity to an ankle and foot human model. Reflection and transmission coefficients (S-parameters), and radiation patterns and efficiency for each of these scenarios are studied and compared. Here, different problems arise such as an inherent resizing of some antenna dimensions, due to the bending process, as well as losses caused essentially by human ankle tissues.

As a first approximation, the initial values with respect to high band and low band radiating element lengths ($L_{LB}$ and $L_{HB}$, respectively) were chosen by taking as reference the quarter wavelength corresponding to the intended central frequencies [27]. These central frequencies of the lowest and highest bands are respectively $f_{LB} = 1.5845 \text{GHz}$ and $f_{HB} = 2.45 \text{GHz}$. The initial radiating element lengths were then reached, by using the well-known expression that relates the speed of light and frequency.

The values for $W$, $h$ and gap were chosen considering the approach in [2], the maximum dimensions of the reference bracelet, and also sufficient margin for parametric study in II-B.

From an ideal perspective, the available metal PEC with a thickness of 0.1 mm was assumed as starting conductor material. Further on, the metal parts of the antenna were modelled with pure copper, with similar electrical properties to the Kapton® material, anticipating that the antenna had to be bent.

The substrate material, used between the radiating elements and ground plane was air. Later, there was a need to insert a different substrate material, a foam with electrical properties similar to the air, and sufficient flexibility and robustness in order to withstand the bending process and fit into the ankle bracelet.

In terms of feeding, the use of discrete ports was the first approach for the simulation process. During all the parametric study, both feeding points were positioned on the same side of the antenna, as close as possible to the gap.

### B. Parametric Study

A minimum goal of -10 dB was chosen for both the reflection and transmission coefficients, around the central frequencies of interest ($f_{LB} = 1.5 \text{GHz}$ and $f_{HB} = 2.45 \text{GHz}$). All the remaining parameters values are fixed, whenever a parameter is swept. The most important conclusions for each parameter sweep are reported.

In relation to height $h$, values of 1, of 2.5 and 4 mm were considered, taking into account that the reference ankle bracelet model has an available height of roughly 5 mm. $S_{11}$ and $S_{22}$ curves, around the central frequencies of interest, are most favourable and wider for higher values of $h$ ($\sim 7.3 \text{ dB and } \sim 4.5 \text{ dB as minimum values, respectively}$). The isolation between ports is bigger for smaller values of $h$, around the two operating frequencies of interest ($S_{21}$ of $\sim -15 \text{ dB}$ and $S_{12}$ of $\sim -28 \text{ dB}$).

For the width $W$, values of 14, 20 and 27 mm were considered, taking into account that the reference ankle bracelet has a width of roughly 35 mm. $S_{11}$ curve shows closer to target results and no frequency shifts, as the width $W$ increases. $S_{22}$ curve is shifted down, as the width $W$ of the antenna increases ($\sim 4.5 \text{ dB as minimum value for both reflection coefficients}$). $S_{21}$ and $S_{12}$ do not show a linear behaviour, as width $W$ varies (similar sequence of minimums, when compared with the result of $h$ sweep).

For the length $L_{HB}$, values of 20.6, 30.6 and 40.6 mm were chosen. As expected, the operating frequencies are shifted down as length $L_{HB}$ increases for both ports. $S_{11}$ and $S_{22}$ plots show a minimum of $\sim -4dB$ around their respective operating frequencies (1.5 GHz and 2.7 GHz, respectively). Again, the same behaviour is observed for the operating frequencies of the transmission coefficients ($S_{21}$ and $S_{12}$), when comparing with the previous parameters sweeps.

In terms of length $L_{LB}$, it was considered values of 40, 50 and 60 mm. $S_{11}$ curve shows closer to target results for
higher values of the length $L_{LB}$. $S_{22}$ is shifted down and the bandwidth is decreased, as the length $L_{LB}$ increases. $S_{11}$ and $S_{22}$ plots show minimums of $\sim-6$ dB and $\sim-4$ dB, respectively). $S_{21}$ and $S_{12}$ are shifted down as the $L_{LB}$ increases.

Finally, the gap influence on the S-parameters was studied. Values of 1, 2 and 3 mm were considered for the gap. The gap affects more the coupling between the two radiating elements. As the gap get smaller, the operating frequency of $S_{21}$ shifts up, while the operating frequency of $S_{12}$ shifts down. $S_{11}$ plot shows closer to target results for lower values of the gap, while $S_{22}$ shows the most favourable antenna performance for higher values of the gap with minimums of $\sim-4.5$ dB.

C. Feed Line and Feed Positioning

In this subsection, the main effects of feed structure and positioning on the S-parameters, as well as their operating frequencies and respective bandwidths were studied.

At a first stage, being always used discrete ports for feeding, a parametric study of feed positioning was carried out. Primarily, different positions were considered with the feed points on the same side (3, as an example); secondly, the feed points on opposite sides were placed in different positions (4); thirdly, the feed points were placed on other alternative positions (5). Noting that the same initial values for the antenna parameters had been assumed.

At a second stage, after reaching the most favourable feed points positioning, a 3D model of a semi-rigid coaxial cable was created, in order to understand if there were significant differences between discrete ports and coaxial cables. Here, the antenna parameters and coaxial cables positioning were optimised, taking into account the before-mentioned goals for operating bands.

1) Feed points on the same side: The parametric study was done with the two feed points placed on the same side, by changing the position of a discrete port and fixing the position of the other one. For this purpose, a parameter sweep for the high band feed point position was carried out with $v \in [0, 29]$ mm, according to Figure 3.

From this parametric study, it can be concluded that $S_{11}$ curves show an irregular behaviour over the frequency, as position $v$ varies. However, it can be observed that for intermediate values ($v \in [10, 22]$ mm) there are closer to target return loss values, being the minimum located at $v = 22$ mm with roughly -30 dB. $S_{22}$ curves show a regular variation for the respective curves along the $v$ axis. As expected, a bigger $v$ yields a most favourable $S_{22}$. $S_{12}$ is shifted up as $v$ increases, while $S_{21}$ is shifted down in frequency and, at the same time, loses its resonance as $v$ increases.

Next, it was assumed to fix the position of the high band port, and then the position of the low band one was swept with $v \in [0, 49]$ mm.

From this parametric study, it was concluded that, in the high band for reflection coefficient ($S_{11}$) there is not a regular behaviour over the frequency. It can be observed, once again, that for intermediate values ($v \in [20, 30]$ mm) there are closer to target return loss values, but always above -4.5 dB. In the low band port for $S_{22}$, there is not a regular variation for the respective curves along the $v$ axis. Only for $v = 30$ mm, $S_{22}$ is below the goal of -10 dB (approximately -40 dB). In terms of transmission coefficients, in the high band port $S_{12}$ is shifted down in frequency and, at the same time, loses its resonance as $v$ increases. Thus, at the lower values of $v$ occurred the closer to target resonance ($S_{12} \in [-40, -60]$ dB for $v \in [1, 10]$ mm, near 2.45 GHz). In the low band port $S_{21}$ has its operating frequency far from 1.5 GHz, being closer to this frequency of interest for lower values of $v$.

After the last two position sweeps, the most favourable positions along the $v$-axis for the ports placed on the same side are $v = 30$ mm and $v = 22$ mm for the high band and low band ports, respectively.

2) Feed points on opposite sides: Three cases were studied as shown in Figure 4. Noting that in case 1 the feed points are placed at opposite sides on a point mid-way along the length of the respective radiating elements. Therefore, the high band feed point is placed at $v = 15.3$ mm, and the low band one is placed at $v = 25$ mm. In case 2 high band and low band ports are placed at $v = 30$ mm and $v = 22$ mm.

(a) Reference case for position of the high and low band ports placed on opposite sides.
(b) Case 1 of the position of the high and low band ports placed on opposite sides.
(c) Case 2 of the position of the high and low band ports placed on opposite sides.

Fig. 4. Feeding points placed on opposite sides.

The most favourable return loss results occur in case 2 with $S_{22} \approx -20$ dB near 1.5 GHz and $S_{11} \approx -12.5$ dB near 2.45 GHz. $S_{21}$ is a little closer to target in case 2 ($S_{21} \approx -14$ dB), but $S_{12}$ is closer to goal in the reference case ($S_{12} \approx -15$ dB).

3) Other positions: Two more cases were studied as shown in Figure 5. Noting that in case 1 the feed points are centred along the width $W$ axis and radiating elements length axis. Therefore, the high band feed point is placed at $u = 10$ mm and $v = 15.3$ mm, and the low band one is placed at $u = 10$ mm.
mm and \( v = 25 \) mm. In case 2 the feed ports are placed at the optimal positions along the v-axis for the ports placed on the same side (\( v = 30 \) mm and \( v = 22 \) mm for high band and low band ports, respectively).

(a) Case 1 of the position of the high and low band ports placed in other positions.

(b) Case 2 of the position of the high and low band ports placed in other positions.

Fig. 5. Feeding points placed in other positions.

Up to this point, there is no solution that satisfies all the goals related to S-parameters and operating bands. However, it is the case 2 of the feed points placed at opposite sides that shows the optimal results, in which \( S_{21} \) is still a little above -10 dB.

4) Effect of coaxial cable: It is used pure copper instead of previous Perfect Electrical Conductor (PEC) material, holding constant the thickness of 0.1 mm for metal parts. In respect to feed line, it is used as reference a semi-rigid coaxial cable with a copper outer conductor (RG405/U-086 [28]). Moreover, it was needed to extend the inner conductor of the coaxial cables from each ground plane to the respective radiating element. As a result of these changes, Figure 6 shows the influence of 20 mm long coaxial cables as feed lines on S-parameters curves for case 2 of the feed points placed at opposite sides. In subsection II-D, this coaxial cable is replaced by another one due to a reason that will be explained there.

Fig. 6. S-parameters for the optimal solution of the high and low band ports placed on opposite positions with 20 mm long coaxial cables.

D. Effect of Defected Ground Structures

At this point, given the parametric studies that were carried out until now did not lead to acceptable results in terms of decoupling, it was crucial to find a way to overcome this problem. From [29], there are two distinct ways of enhancing the isolation/decoupling for dual or multi-port antennas: changing or redesigning the antennas structure, or by adding an external microwave feed network to the antenna without making any changes to the already designed antenna structure.

The first approach was the concern of this project because the second approach would have required more physical space and the use of transmission lines as decouplers. Within this context, there were two distinct cases to take into account: operating frequency bands are sufficiently widely separated; or operating frequency bands have to be closely spaced or even have to occupy the same band such as Multiple Input Multiple Output (MIMO).

In this project, given the fact that the two operating frequency bands of interest are approximately separated by 1 GHz, the first case is the matter of interest. Decoupling enhancement can be achieved by separating the feeding ports and/or the radiating elements by multiples of half a wavelength. However, there are physical space limitations. Thus, it is needed to find an appropriate decoupling technique. To summarise, there are three distinct techniques that were found in the literature: sharing a loaded ground plane with resonant defects such as slots, slits and/or stubs [29], [30]; introducing split-ring resonators between closely-separated antennas [29], [31], [32]; augmenting the common area of the ground plane, between the antennas, with Electromagnetic Band Gap (EBG) structures. In this project, the use of slots is taken into account, for purposes of simulation and test. The use of EBG structures was discarded as an option.

1) Horizontal Slots: Simulation results are presented, by using horizontal slots placed at the ground plane, near the low band feeding port. Given the fact that only the \( S_{21} \) parameter is above -10 dB, the physical length of the slots are dimensioned with a quarter-wavelength long, at approximately the central frequency of 1584.5 MHz. After doing some slight changes in respect to the dimensions, placement and number of slots, the effect of the horizontal half-wavelength slots was then studied, by showing figures with the surface current density distribution in the antenna. Figure 7 shows the three different configurations of interest with horizontal slots placed near the low band feeding port.

Simulations for two different coaxial cables: the above-referred semi-rigid one with a copper outer conductor (RG405/U-086 [28]), and the coaxial cable (EZ 47-TP/M17 [33]) were done. This change was done because it would be necessary to have thinner coaxial cables in order to fit the reference bracelet. To that end, both the antenna and the coaxial cables must be bent.

Fig. 7. Defected ground plane with horizontal slots.

Apart from the decoupling enhancement of the low band
port, a new resonance frequency is created, at approximately 2.75 GHz, by introducing the slots on the ground plane. In conclusion, there is no significant difference to report in terms of enhancement of $S_{12}$ around 2.45 GHz, when comparing the used number of slots. This technique improves the low band port isolation ($S_{12}$) by approximately 23 dB. Furthermore, the replacement of coaxial cables affects more significantly the reflection coefficients. There are sharper resonance peaks in $S_{11}$ curves with the coaxial cable 2, and the use of the coaxial cable 1 causes sharper resonance peaks in $S_{22}$ curves.

Fig. 8. $S$-parameters for the optimal solution of defected ground plane with three slots.

Figures 9 and 10 show how the RF surface electrical currents flow through the defected ground plane and radiating parts of the antenna, at the two frequencies of interest (1.5 GHz and 2.45 GHz).

(a) SCD Range. (b) SCD on the ground plane (2.45 GHz). (c) SCD on the ground plane (1.5 GHz).

Fig. 9. Simulated SCD distribution on the ground plane for the antenna with three horizontal slots on the ground plane, being fed by the coaxial cable 2.

Fig. 10. Simulated SCD distribution on the radiating patches for the antenna with three horizontal slots on the ground plane, being fed by the coaxial cable 2.

Figure 9(c) shows how the system of three slots acts as a band-stop filter at 1.5 GHz. Figure 10(b) demonstrates how

the isolation enhancement of the low band port translates itself into a most favourable surface current density on the radiating element dimensioned for 2.45 GHz.

The antenna far-field radiation characteristics are studied for the case of three slots. Figure 11 shows the standard set of coordinates used for the graphical representation of the antenna 2D radiation patterns (gain in decibels). The presented values of gain are normalised to the highest value of the simulated results.

Fig. 11. Set of coordinates to evaluate the radiation patterns in the flat antenna.

Fig. 12. Radiation patterns for constant $\Phi$, $\Phi = 0^\circ$ (xz-plane).

Fig. 13. Radiation patterns for constant $\Phi$, $\Phi = 90^\circ$ (yz-plane).
In xz-plane, in respect to both centre frequencies, the presented radiation patterns show that the antenna exhibits a quasi-omnidirectional behaviour. In yz-plane, the radiation patterns, at 1.5 GHz, are almost dipole-like with large back lobes. Using the classical dipole radiation pattern, as a reference point for comparison, it can be noted that there is some resemblance to this antenna, in relation to xz (H-plane) and yz (E-plane) patterns. This similarity to dipole radiation patterns is more visible at the lowest frequency. Moreover, the xy-plane pattern looks quasi-omnidirectional, even considering some asymmetry caused by the geometry and feed positioning.

In relation to the antenna with three horizontal slots, at 1.5 GHz, the estimated radiation efficiency is $\sim 96\%$ and, considering the impedance mismatch loss of the antenna when connected to the coaxial cable, the antenna estimated total efficiency is $\sim 87\%$. At 2.45 GHz, the antenna radiation efficiency is $\sim 84\%$ and its total efficiency reduces to $\sim 75\%$. As a conclusion it is inferred that the solution with horizontal slots (8) shows better results than this solution with diagonal slots. For this reason, it was decided to not present figures for simulated radiation patterns and surface electrical currents flow through the defected ground plane and radiating parts of the antenna (as done in the last subsection). In next subsection, the experimental setup will take into account the solution with three horizontal slots.

### E. Experiment Setup and Results

In this subsection, the antenna is measured in a flat condition, i.e., without any applied deformations. S-parameters and the operation bands are presented. This experimental step was performed in the Radio-Frequency (RF) Laboratory using a Vector Network Analyser (VNA) E5071C from Agilent Technologies. The final prototype was connected to the VNA through an RF cable with the aid of a 50 $\Omega$ SubMiniature version A connector, which was soldered on the antenna.

Fabrication method consisted on using the photolithography technique, in which an etching chemical process radiation is carried out to shape the Kapton®copper [34] to the intended geometry, from the use of a photo-resistive solution, sensitive to ultraviolet rays. Additionally, a very low permittivity foam was used to give mechanical robustness without affecting the electrical properties of the antenna. The Computer Simulation Technology (CST) layout can be seen in Figure 16(a). And besides, Figures 16(b) and 16(c) show different views of the antenna prototype.

![Fig. 15. Defected ground plane with diagonal slots.](image)

2) Diagonal Slots: This subsection shows the simulation results by using diagonal slots placed on the ground plane, approximately centred in the proximity of the gap between the radiating elements. The physical length of the slots is once again dimensioned with a quarter-wavelength long at approximately the central frequency of 1584.5 MHz. Figure 15 shows the three different configurations of interest with diagonal slots placed near the low band feeding port.

![Fig. 16. Final prototype of the flat antenna and measurement scenario.](image)

As can be seen in the experimental results presented in Figure 17 and taking into account the operating bands of interest, the antenna prototype shows a -10 dB impedance bandwidth that does not properly cover all the frequencies of interest.
There is a frequency downshift in the bands of interest, which is much more pronounced in the lowest band (200∼300 MHz, approximately), while in the highest band there are variations of approximately 50∼100 MHz. Contrarily to this frequency downshifting behaviour, the resonance peak of decoupling has a frequency upshift of approximately 400∼500 MHz.

III. ANTENNA INTEGRATION IN AN ANKLE BRACELET

A. Reference Ankle Bracelet

One of the most pertinent ways the bracelet device materials could influence in antenna performance is by means of their dielectric properties. A 3D model must be built, with a suitable choice of materials, in order to emulate a real case. To that end, it is used a GPS ankle bracelet device based on a commercial company. Figure 18 shows the 3D CST model of the reference ankle bracelet and the bent antenna.

![Fig. 18. Reference ankle bracelet and bent antenna.](image)

In spite of seeming to have a cylindrical geometry, this ankle bracelet features an elliptical geometry. In fact, it is “elliptical ring-shaped”, in which its width is along y-axis, its height is along z-axis, and their semi-major and semi-minor axis are along y-axis and x-axis, respectively. The values of their parameters are the following ones (mm): outer semi-major axis (50), outer semi-minor axis (45), inner semi-major axis (45), inner semi-minor axis (40), width (6) height/spacing (35) and rings thickness (1). Furthermore, the 3D CST model of the reference ankle bracelet is composed of a common thermoplastic polymer, called ABS, with an electrical permittivity of 2.8.

B. Effect of Bending and Casing

In fact, it is very difficult to assure a flat antenna when applied to non-flat devices, due to the fact that these antennas must adapt their geometry to the surface in which they are placed on and, at the same time, guarantee a certain user’s ease and freedom of movement. Furthermore, the evaluation of antenna performance under deformation scenarios is a key factor to the operation in the vicinity of the human body.

Throughout the simulations in a bending scenario, an ellipsoidal structure had to be attached on the antenna back-side ground plane, in accordance with the shape of the reference ankle bracelet. The robustness of the antenna under a bending scenario would be guaranteed with the same low permittivity foam used in the experimental stage, although it would have to be resized to accommodate the geometry change. However, this foam was not included in the simulations, as it is not expected to affect the electrical properties of the antenna. In relation to the feed line used through the simulations, it was necessary to replace the EZ47-TP/M17 coaxial cable by discrete ports. Apart from being easier to integrate into the 3D CST model of the ankle bracelet, it does not cause significant impact on the antenna performance.

1) S-Parameters: In relation to the bending scenario, the resizing of the antenna dimensions in accordance with the curved structure of the ankle bracelet caused an operating frequency downshift (1.22 GHz and 2.32 GHz).

Apart from the evaluation of return loss and -10 dB operating bands of interest under a bending scenario, it is also important to evaluate the antenna performance in casing scenario. The presence of the whole reference ankle bracelet caused a small frequency downshift, when compared to free-space and bending scenarios (1.16 GHz and 2.24 GHz). In fact, structures covering antennas, usually called radomes, are composed essentially of plastic material, which in turn downshifts their operating frequencies. Plastic has a higher dielectric constant than air. Therefore, the relative proximity of the plastic makes the antenna see a higher effective dielectric constant, leading to an increase of the electrical length of the antenna, as well as a reduction of the operating frequencies.

2) Radiation Patterns and Efficiency: Regardless of the bending process for both the downshifted operating frequencies, (1.22 GHz and 2.32 GHz), the shape of radiation patterns remain almost the same. At these two frequency points, bending deformations have no significant influence in the antenna radiation patterns shape, when compared with the radiation patterns of the flat antenna in free-space (see Figure 11). Using again the classical dipole radiation pattern as reference point, this antenna can be seen as a dipole antenna, with its length along the x-axis. The xy-plane pattern (E-plane) looks like a dipole, and the yz-plane pattern (H-plane) looks quasi-
omnidirectional, even considering some asymmetry caused by the geometry and feed positioning. This similarity is still more visible at the lowest frequencies. At the goal operating frequencies (1.5 GHz and 2.45 GHz), the resonance is lost, as seen before, which in turn leads the antenna to lose the dipole behaviour (see Figure 4.8). This loss is more visible in the xy-plane pattern (E-plane). In relation to the bent antenna, at 1.22 GHz, the estimated radiation efficiency is $\sim 100\%$ and the estimated antenna total efficiency is $\sim 96\%$. At 2.32 GHz, the antenna radiation efficiency is $\sim 84\%$ and its total efficiency reduces to $\sim 82\%$. In comparison with the simulation results for the flat antenna (in the end of the subsection II-D1), there is a gain increase caused by the ellipsoidal structure, noticeable in the highest operating frequency.

Again, when comparing these radiation patterns with those of the flat antenna in free-space (see Figure 11), it can be concluded from Figure 4.9 that this antenna can still be seen as a dipole antenna, despite of the bending and casing processes, for both the downshifted operating frequencies. The xy-plane pattern (E-plane) looks like a dipole pattern, and the yz-plane pattern (H-plane) looks quasi-omnidirectional. This similarity is more visible at the lowest frequencies. The similarity to dipole is lost, for the goal operating frequencies, 1.5 GHz and 2.45 GHz. In relation to the bent and cased antenna, at 1.16 GHz, the radiation efficiency is $\sim 100\%$ and the antenna estimated total efficiency is $\sim 94\%$. At 2.24 GHz, the antenna estimated radiation efficiency is $\sim 87\%$ and its total efficiency reduces to $\sim 81\%$. In comparison with the simulation results for the only bent antenna, the whole casing does not lead to significant differences.

C. Biological Model

Unlike the voxel models, which are complex and demands longer computer times, simplified models are sufficiently suitable to predict how the antenna under study performs in close proximity to the human body. In order to decrease the computational effort associated with a full human model, a four tissue layered human model with a simplified geometry shape was considered appropriate, and a single-layered model was taken for the ankle and foot (see Figure 19).

The ankle model consists of a 20 mm long elliptical model, and four tissue layers which represent bone, muscle, fat, and skin. Based on previous simulations, it was concluded that a more detailed biological description of the foot was not very influential, so it was decided to use an even more simplified model by considering the foot as a single-layered brick. The foot model consists of a brick model with 250 x 76 x 40 mm, which represents bone. The thicknesses of each body tissue layer that compose the ankle model are the following ones (mm): skin (2), fat (10), muscle (20) and bone (11 of major axis).

Accurate modelling of any real body part requires the dispersion characterisation of each body tissue, in respect to operating frequency range of the antenna under study. To that end, in order to evaluate the Specific Absorption Rate (SAR), the values for body tissues density are the following ones (kg.m$^{-3}$): skin (1100), fat (910), muscle (1041) and bone (1850).
A significant difference of return loss, when the suggested antenna is cased by the ankle bracelet and placed close to the human ankle and foot model, is observed. For a distance of 2 mm between the ankle bracelet and the biological model, the results show that the lowest operating frequency is shifted downwards from 1584.5 to 1291.9 MHz, in comparison with the free-space curve. The highest operating frequency is also shifted downwards from 2447.5 to 2187.8 MHz, in comparison with the free-space curve. Both modulus of $S_{11}$ and $S_{22}$ decreased, due to the expected losses caused by human body. In relation to the mutual S-parameters, both peak frequencies are lost but are still below -10 dB.

2) Radiation Patterns: Here, the antenna far-field radiation characteristics in the vicinity of the proposed biological model are studied. Figure 24 shows the standard set of coordinates used for the graphical representation of the antenna 2D radiation patterns (gain in decibels).

When comparing these radiation patterns with those of the flat antenna in free-space (Figures 12, 13 and 14), as well as
the radiation patterns of the antenna in bending and casing scenarios, it can be concluded that the patterns in xz-plane, yz-plane and xy-plane modify their shapes and the gain is reduced, due to the proximity of the biological model of the ankle and foot. This happens for both the downshifted operating frequencies, 1.29 GHz and 2.19 GHz, and the goal operating frequencies, 1.5 GHz and 2.45 GHz. However, here are only presented the radiating patterns of the downshifted frequencies (see Figures 27, 25 and 26).

Simulated radiation efficiency and total radiation efficiency show that their maximums occurred at the highest downshifted frequency (f = 2.19 GHz), with values of ~-8.1 dB (~15%) and -8.4 dB (~14%), respectively. The radiation efficiency and total radiation efficiency, at the lowest downshifted frequency (f = 1.29 GHz) reached values of ~-7.3 dB (~13.6%) and ~-8.8 dB (~13.2%), respectively. Here, it is possible to see a big decrease in terms of radiation efficiency, when comparing with all the previous results, due to the absorption by the human ankle tissues.

3) Levels of SAR: The effects of the proposed biological model on levels of SAR are analysed. Since the antenna under study was designed for wearable applications, it is crucial to evaluate the effects of EM fields near the human body. In order to accurately calculate the values of SAR caused by the antenna, there are some aspects that should be taken into account, namely the conductivity, geometry and mass density of the body part exposed to certain electric field strengths, depending on the relative position to the antenna. According to ICNIRP, extremities such as hands, wrists, feet, and ankles, higher levels of SAR up to 4W/kg for any 10 g of tissue are permitted [35]. Noting that the ankle bracelet was placed 2 mm far from the four-layered human ankle model.

Values of SAR depend on the conductivity of the human body tissues, which in turn depends on the operating frequency. Although the proposed antenna is not meant to be used in the transmission mode with significant power at the Radionavigation Service bands, a SAR evaluation has been performed.

For a default input power of 1 W, the 3D Maximum of SAR, considering 10g of tissue, has occurred at the highest downshifted operating frequency (f = 2.19GHz) with a value of 2.814W/kg (as shown in Figure 28(b)).

Taking into account the objectives of this project, the antenna should have good performance in free-space and non-free-space conditions, in terms of operating frequencies, bandwidth and radiation efficiency. The miniaturisation of the antenna structure to fit into a commercial ankle bracelet model was accomplished. Even though some undesired frequency shifts in the bands of interest were observed (as seen in Subsection II-E), the fabrication and S-Parameters test results of the antenna prototype in a free-space scenario led to a reasonable agreement with the S-Parameters simulation results. The antenna prototype with three slots on the ground plane near the low band port was elected as the most suitable design. Section III showed that the simulated results of the antenna in non-free-space conditions (bending, casing and human body proximity) were promising for a proof-of-concept.

REFERENCES


