Wallet Flexible Antenna Project

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To my wife and daughter.
“The science of today is the technology of tomorrow” – Edward Teller
ACKNOWLEDGEMENTS

Firstly I would like to offer my sincerest gratitude to my supervisor, Professor António Moreira, for all the support, comprehension, guidance and example that has inspired me throughout the development of this work.

I further wish to dedicate this thesis to my beloved wife and daughter. Their support has been bracing my strength and perseverance.

I would also like to thank all my family, who made it possible for me to reach this milestone in my life and complete my journey as an Engineering student.

To conclude, I would like to thank my friends João Maurício and Francisco Pires for the fundamental friendship during the past years.
Abstract

Scientific research and consequent technological evolution have been the increasing drive to innovation in a vast number of fields. Wearable antennas have been fairly studied and tested, presenting already a wide range of uses in different industries such as Medical, Military and Entertainment.

This work focuses on the development of a wearable flexible antenna with a disc monopole shape, built on Kapton®, tuned to operate in the Industrial, Scientific and Medical (ISM) band. The antenna was thought to be held inside a wallet – for this reason it was simulated and analyzed the effects of bending, inside the referred wallet and finally in the vicinity of the human body.

Several antennas were studied in order to obtain the optimized characteristics of the prototype built in this work. The main goal of this work is to design, build and test a proof of concept of an antenna prototype for the ISM 2.4 GHz band, which can be used inside a wallet with acceptable performance for applications.

Key words: Wearable antennas, Flexible Antennas, Coplanar Waveguide (CPW), Industrial, Medical and Scientific (ISM), Circular Monopole Disc, Kapton®
RESUMO

A investigação científica e a consequente evolução tecnológica têm sido o factor principal na inovação de um vasto número de áreas. Antenas a operar junto ao corpo humano tem sido uma dessas áreas, apresentando um variado número de aplicações em diferentes indústrias tais como Medicina, Militar e Entretenimento.

Este trabalho foca-se no desenvolvimento de uma antena flexível e a utilizar junto do corpo humano, cujo formato é um disco circular monopolo, construído em Kapton® para operar na banda Industrial, Científica e Médica. A antena foi pensada em ser utilizada dentro de uma carteira – para tal foi testado analisado os efeitos de deformação, dentro da referida carteira e na proximidade do corpo humano.

Várias antenas foram estudadas com o objectivo de alcançar as características óptimas do protótipo estudado e construído neste trabalho. O objectivo principal deste trabalho foi projectar e testar, como prova de conceito, um protótipo de antena para a banda ISM 2.4 GHz, que pode ser usada dentro de uma carteira com desempenho aceitável para a aplicação.

Key words: Antenas a operar junto ao corpo, Antenas Flexíveis, Guida de Onda Coplanar (CPW), Banda Industrial, Científica e Médica (ISM), Disco Circular Monopolo, Kapton®
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<td>BAN</td>
<td>Body Area Network</td>
</tr>
<tr>
<td>CPW</td>
<td>Coplanar Waveguide</td>
</tr>
<tr>
<td>CST</td>
<td>CST Microwave Studio</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FSA</td>
<td>Flexible Substrate Antenna</td>
</tr>
<tr>
<td>HBC</td>
<td>Human Body Communications</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>MICS</td>
<td>Medical Implant Communication Service</td>
</tr>
<tr>
<td>NB</td>
<td>Narrow Band</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SAR</td>
<td>Specific Absorption Rate</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wideband</td>
</tr>
<tr>
<td>WBAN</td>
<td>Wireless Body Area Network</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WMAN</td>
<td>Wireless Metropolitan Area Network</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>WWAN</td>
<td>Wireless Wide Area Network</td>
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1 INTRODUCTION

This chapter contains a brief introduction about the scope and importance of flexible wearable antennas to operate in the vicinity of human body and the motivation that led to the subject of this thesis. The main objective of this work, as well as its structure, will also be presented in this chapter.
### 1.1 Background and Motivation

Wireless communication technology has been increasingly impacting our lives since the ending of the twentieth century. The technology rooted on wireless communications has several advantages, such as mobility, flexibility, convenience, ease of use and lower cost.

In figure 1.1 it is possible to note the types of wireless networks, in four specific groups, accordingly to their signal range and applications.

The first and broader range group is Wireless Wide Area Network (WWAN). It employs the network infrastructure of mobile operators by means of which they provide a coverage of a wide range by wireless connection. The second group, Wireless Metropolitan Area Network (WMAN), enables users to connect through multiple locations within a metropolitan area. In this group the technology most frequently used is Worldwide Interoperability for Microwave Access (WiMAX). The third group, Wireless Local Area Network (WLAN) enables wireless connection within limited areas, such as office building, schools, universities, etc. WLANs have come to be generally called Wireless Fidelity (WiFi).

The last group, Wireless Personal Area Network (WPAN), is a network for inter-connecting the devices that operate within this network area.

![Figure 1.1: Wireless network range.](image)

Within the WPANs, it is possible to distinguish a specific network, called Wireless Body Area Network (WBAN), which enables devices to communicate with each other by implanting them on human body [1]. These wireless networks and their respective range are illustrated in Figure 1.2.
In the last years, there has been an increase of interest in research and development of WBANS technology, also designated as Body Sensor Network (BSN) or simply Body Area Network (BAN).

IEEE 802.15 defines Body Area Network (BAN) as “A communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics / personal entertainment and other” [2]. IEEE 802 established 802.15.6 for the standardization of WBAN.

A BAN consists of different nodes attached to different body parts or attached to different bodies. These nodes can communicate with each other and transmit data to a remote server. These nodes are constituted by sensors which have an antenna responsible for the transmission and receiving data. There are innumerable applications within BAN such as medical, military, security, etc. The wearable antennas used in BANs act as a transceiver to send and receive the information and therefore they should be kept flexible in order to not conditioning the movements of human body.

These antennas must comply with the following characteristics:

- Compact size and light weight
- Flexible
- Keep radiation away from the human body
- Stable performance in the human body vicinity

Regarding the position of the communicating devices it is also important to discriminate the different type of communications, which is illustrated in Figure 1.3:
- On Body Communications: The communication is performed by devices that are located on the body of the same person
- In Body Communications: The communication occurs between a device implanted in the body and other inside or on body (in in and in on communications respectively)
- Off Body Communications: The communication occurs between a device placed on body and an external device (e.g. router) placed outside it
- Body to Body Communications: The communication is performed by devices placed in two different bodies

Figure 1.3: Different types of communication for Body Area Network.

Another important issue when studying and analyzing these antennas is the band of operation. There are several operation bands that can be used, each one with particular advantages and disadvantages. In Figure 1.4 is possible to observe the different frequencies defined by IEEE 802.15.6 with reference to the respective countries, in the case of the same band being used in different frequencies for different countries. Accordingly to [3] “IEEE 802.15.6 standard defines three PHY layers, i.e., Narrowband (NB), Ultra wideband (UWB), and Human Body Communications (HBC) layers. The selection of each PHY depends on the application requirements”.

Figure 1.4: IEEE 802.15.6 WBAN frequencies.
In order to improve the communications between devices or systems within BANs, it is necessary to continue the research and development of its components, in particular the antennas. These antennas can be integrated in a common item, being designated as Wearable Antennas, which leads to multiple possible applications. These applications must attend to the users’ needs nowadays, which implies practical and efficient solutions. Part of this efficiency and practical use is to incorporate an antenna in an item that is generally used daily, allowing new applications to the user without the need to acquire an extra device. For this study we considered this commonly used item as a wallet.

1.2 Objectives

The objective of this work is to build an antenna prototype to be used in BANs. It is necessary to analyze, design and test wearable antennas in a flexible substrate, in order to obtain the desired new work subject – an antenna to be used in a wallet. With the aim of testing the performance of this prototype, the two main characteristics of this antenna, being wearable and flexible, must be studied and evaluated. Tests and measurements regarding its flexibility, bending the antenna, are to be performed, as well as tests and measurements in the vicinity of the human body and inside a wallet, in order to guarantee the desired requirements and reach the goals of this work.

1.3 Contents

This thesis is structured in six chapters.

This chapter includes an introduction to the subject under analysis, as well as its objectives and structure.

In chapter two, the state of art of wearable antennas is described, analyzing some studies that were performed in different bands, in order to justify the choice of the band and feeding technique for this work.

Chapter three contains the state of art of flexible antennas, analyzing studies on different shapes of antennas and substrate, leading to the choice of the final substrate and shape.

Chapter four contains the design steps, simulations, and tests of the antenna that will be used for this Thesis.

Chapter five describes the performance of the selected antenna inside a wallet.

Finally, the main conclusions are presented in chapter six. The perspective for future work on this topic is also given throughout this chapter.
2 WEARABLE ANTENNAS

This chapter discusses the importance and challenges of wearable antennas in recent technology. A literature review of the wearable antennas is presented with the complementarity of analysis for different wearable antennas, in different operations bands.
2.1 Introduction to Wearable Antennas

In order to achieve success in the design and test of a wearable flexible antenna, it is important to understand the main characteristics and challenges of wearable antennas. These must comply with requirements such as the insensitivity to detuning in the presence of the human body, maintaining their efficiency in the presence of the human body and reducing the Specific Absorption Rate (SAR), in order to be able to achieve required performances. It is also critical to highlight the importance of the wearable antennas capability to maintain their efficiency when bent, due to human body shape and movement, which refers to the flexibility of the antenna.

As described in the previous chapter, it is possible to have different bands of operation, being UWB and ISM the most commonly used for wearable antennas. Several wearable antennas were studied, but for the purpose of this work, only few were selected to be presented, which required more analysis since it can influence the decision of some of the characteristics of the prototype antenna to-be.

2.2 UWB Antennas

UWB is an operation band with several applications that has been under research for the past decades, since the FCC enabled rules for the utilization of data communications, radar and safety applications in this band [4].

In [5] a vertical disc monopole, named due to its disc radiator being vertically placed on the ground plane, was designed and studied. This simple shape, which is one important characteristic to consider when building an antenna, was designed and tested. In Figure 2.1 it is possible to perceive the design of this vertical disc monopole.

![Figure 2.1: Design of the antenna from [5]: (a) three-dimensional view; (b) side view.](image)
In [5] it was also built a prototype based on design showed in the previous figure, which can be observed from different views in Figure 2.2.

![Figure 2.2](image)

Figure 2.2: Prototype antenna from [5]: (a) front view; (b) side view.

The dimensions of this vertical disc monopole studied in [5] should also be presented and studied, since it will be one of the first and determinant steps in the designing of the antenna for this work. In Table 2.1 is listed the dimensions of the vertical disc monopole that will have impact on the designing process.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Letter</th>
<th>[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>W</td>
<td>100</td>
</tr>
<tr>
<td>Length</td>
<td>L</td>
<td>100</td>
</tr>
<tr>
<td>Radius</td>
<td>R</td>
<td>12.5</td>
</tr>
<tr>
<td>Feed Gap Height</td>
<td>H</td>
<td>0.3 – 0.7</td>
</tr>
</tbody>
</table>

Table 2.1: Dimensions of the vertical disc monopole from [5].

As referred, in the design of an antenna, analyzing the impact that changing one of the dimensions has in its performance, is critical to achieve a well dimensioned antenna.

In the simulations in [5] it was verified that the performance of the antenna was mainly dependent on the feed gap height and ground plane dimensions as it is possible to see in Figure 2.3, where the return loss factor was compared for each dimension.

![Figure 2.3](image)

Figure 2.3: Return loss comparison for [5]: (a) width variation; (b) length variation; (c) feed gap variation.
In a second stage of the study performed in [5], after a proper dimensioning of the antenna, it was measured the return loss factor for two different prototypes, which allowed to infer the differences resulting from having different dimensions. The return loss factor comparison between simulation and measurements is a key factor for comparing the frequency operation of the antenna and obtain conclusions for simulations vs measurements. The simulations and measurements of the vertical disc monopole can be observed in Figure 2.4

![Return loss measurement and simulation curves for vertical disc monopole from [5] with different dimensions: (a) r=12.5mm, h=0.7mm and W=L=100mm; (b) r=12.5mm, h=0.7mm, W=100mm and L=10mm.](image)

To comply with the wearable factor, an antenna must be also tested in the presence of a human body in order to evaluate if the antenna’s performance achieves the requirements. In [6] was designed an antenna, to operate in UWB, with a dome shape, as observed in Figure 2.5.

![Dome shaped antenna from [6]: (a) geometry of the antenna; (b) prototype of the antenna.](image)

In this work it was measured the prototype in different distances from the human body to demonstrate the impact of the human body in the frequency of the antenna. This comparison of measurements showed the dielectric loading effect of the body on the antenna, as observed in Figure 2.6.
Figure 2.6: Reflection coefficient measurement and simulation for [6]: (a) free space; (b) in vicinity of the human body.

As mentioned, there are several studies of antennas in this operation band, with successful results, as the ones reviewed in this chapter. These two studies were the most relevant to be used as starting point for the scope of this work and eventually the prototype choice.

2.3 Antennas for ISM

There are also several studies that proof the usefulness of developing antennas within the ISM band that can operate in the vicinity of the human body. The fields that should be evaluated are described above in [5], so several comparisons were made regarding these fields. Here is listed the ISM antennas that were studied and served as base for this work, analyzing the results from each study.

In [7] a coplanar antenna working at 2.45 GHz ISM band was designed with the dimensions and geometry shown in Figure 2.7.

Figure 2.7: Antenna studied in [7]: (a) geometry with dimensions in mm; (b) prototype.
This antenna was simulated in the vicinity of the human body with two different models of human body, a rectangular and an elliptical. The tests were made with the antenna in the arm, in the arm with jacket and in the arm with wet jacket. Results can be observed in Figure 2.8

![Figure 2.8](image1.png)

Figure 2.8: Measurement of reflection coefficient of the antenna in arm, arm with jacket and arm with wet jacket and simulation in the presence of elliptical and flat model of the arm studied in [7].

Regarding the simulation tests in the proximity of human body, it is necessary to consider different models of human body to assure that simulations can be accurate to the measurements in the vicinity of the human body, as shown in Figure 2.9 from the study in [8].

![Figure 2.9](image2.png)

Figure 2.9: $|S_{11}|_{dB}$ sensitivity to the gap between the antenna and the arm model when the antenna is place along the arm length studied in [8]: (a) rectangular human arm model; (b) flat human arm model; (c) elliptical human arm model.

These results demonstrate the impact of each type of model in the antenna's reflection coefficient. It is possible to observe a similarity in the results, concluding that the shape of the human arm, for simulation purposes, can be estimated from the three models.

There are several items that can be adapted to integrate an antenna, like the wallet proposed in this work. In [9] it was designed and tested an antenna that was meant to be used as part of a belt. The design and the prototype of this work are shown in Figure 2.10.
Figure 2.10: Antenna simulation model and prototype from [9]: (a) model front side; (b) model back side; (c) prototype front side; (d) prototype back side.

In order to perform the tests, according to the different situations when using this item, two different situations combined with different users, male and female, were reported in this work. The situations that were analyzed are describe in the Table 2.2.

<table>
<thead>
<tr>
<th>Measured Situation</th>
<th>Detail</th>
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<tr>
<td>MS 1</td>
<td>User standing up. No contact forced between the jeans button and the metal buckle</td>
</tr>
<tr>
<td>MS 2</td>
<td>User sitting. No contact forced between the jeans button and the metal buckle.</td>
</tr>
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Table 2.2: Different scenarios studied in [9] for measurements.

In Figure 2.11 it is possible to observe the results for both situations and for different users.

Figure 2.11: Return loss from [9] for: (a) Tightened belt on air. (b) Male user for MS 1 (c) Male user for MS 2 (d) Female user for MS 2; (e) Female user for MS2

For the ISM band, there is also a variety of studies regarding wearable antennas, which were analyzed for this work, being the ones described in this chapter the most relevant.
2.4 Conclusions

In this chapter it was studied and analyzed wearable antennas within the most common operation bands for these types of antennas, ISM and UWB. For this work, it was chosen to build the antenna prototype to operate in the band ISM. Since the human body is responsible for attenuating the signal of the antenna, it was decided to choose a band which allows greater coverage. Although the channel capacity is higher for small distances in UWB, the coverage of this prototype will be higher if operating in the ISM band. In order to obtain this increase of the distance of the signal’s transmission in the vicinity of the human body, it is also necessary to build a prototype compact in size.

Initially it was studied the dimensioning of an antenna and the impact that the some of the major dimension have in the performance of the antenna, namely the return loss. Posteriorly, it was analyzed the modeling of the human shape for simulation purpose, in order to determine the accuracy of the results for comparing with measurements in the vicinity of the human body. The return loss comparison for simulations and measurements in the vicinity of the human body were also highlighted in this chapter, since it is one of the key factors to study in the scope of this work.

This work aims to test an antenna inside an item, generally used by a person, a wallet, therefore it was also analyzed a study regarding a prototype antenna built inside an item, also used by a person, which is a belt.

It was used a circular disc monopole antenna, as base, for the shape of the prototype in this work, studied and analyzed in [10]. This shape has the advantage of having parameters that can be easily dimensioned, when compared with the other shapes in the works studied, in order to obtain an antenna that achieve the objective of operating in the band ISM inside a wallet. In [10] it was also used the CPW feeding technique, which will also be applied in this work, eliminating the need of having a copper foil in the backside of the prototype antenna and therefore keeping it thin with the purpose of having an antenna with reduced dimensions inside the wallet.
This chapter discusses the importance of the antenna’s flexibility. A literature review of flexible antennas is presented, focusing on the importance of the substrate choice for these antennas with the complementarity of analysis for the effects of bending.
3.1 Introduction to Flexible Antennas

Flexible antennas reached a level of maturity in complying with the necessary flexible requirements for keeping the antennas’ performance, such as the effects of bending. Besides the capability of an antenna to operate in the vicinity of a human body, flexibility is equally relevant, since the antennas in human models, can’t have a rigid characteristic that compromises its performance.

In this context, one of the more important topics to consider is the flexible substrate antennas (FSA), since they play one of the most important roles in the integration of the antenna’s design to be used in wireless devices and sensors. The antennas built upon flexible substrates have the challenge of keeping the desired performance, regarding the resonant peak frequency, when bent or even harder effects, such as stretching and twisting.

From [11], a compilation of 13 peer-reviewed articles regarding flexible substrates, it can be analyzed different fabrication processes, with respective innovation in this field, which must take always in consideration factors such as cost effectiveness.

For the purpose of this work, it is described and highlighted the effects of bending, as well as the choice of the flexible substrate to consider in the construction of the prototype antenna.

3.2 Effect of Bending a Disc Monopole

Another motivation for this work was based on [12], where a coplanar waveguide circular disc monopole, with similarity to the shape selected for this work, built upon the substrate hypalon coated Dacron ($\varepsilon_r = 3$) was tested for bending effects. For this exercise it was necessary to have different angles of bending. These angles can be obtained by shaping a cylinder next to the antenna and bend the antenna to the cylinder. Removing the cylinder, responsible for the bending degree of the antenna, it is obtained a model of the antenna bent in free space.

First it is necessary to state what is called bending degree and how was obtained the different types of bending degrees. Considering the substrate as a rectangle with dimensions $W[\text{mm}] \times L[\text{mm}]$, referring to width and length respectively, one of this dimensions will be part of the cylinder perimeter, depending if the bending is accordingly to $xx$ axis or $yy$ axis.

If the bending is tested accordingly to $xx$ axis, the relationship between the bending degree $bd$ desired and the radius of the cylinder $r$ is:

$$bd^\circ = \frac{360^\circ \cdot W}{2\pi r} \Leftrightarrow r = \frac{360^\circ \cdot W}{bd^\circ \cdot \frac{2\pi}{2\pi}}$$

$$bd^\circ = \frac{360^\circ \cdot W}{2\pi r} \Leftrightarrow r = \frac{360^\circ \cdot W}{bd^\circ \cdot \frac{2\pi}{2\pi}}$$ (3.1)
On the other side, if the bending is to be tested accordingly to the $yy$ axis, the relationship between the bending degree $bd$ desired and the radius of the cylinder $r$ is:

$$bd^\circ = \frac{360^\circ \frac{L}{2\pi r}}{r} \iff r = \frac{\frac{360^\circ}{bd^\circ} \frac{L}{2\pi}}{r}$$ (3.2)

In [12] the effects of bending were tested in the $xx$ axis, as observed in Figure 3.1, for different bending degrees.

The different tests for each bending degree can demonstrate the variation of the parameter $|S_{11}|$ to understand the limitations of the designed antenna. These results can be observed in Figure 3.2.

The results obtained show a decrease in the $|S_{11}|$ parameter proportional to the bending degree, but resulting in good results for the operation band desired in all tested scenarios. Accordingly to this analysis, this circular disc monopole demonstrated effectiveness within the flexibility characteristic.
3.3 Effects of Bending Kapton® Substrate

In order to test one of potential flexible substrate to be used for this work, it was studied the antenna in [13]. This antenna was built upon Kapton®, through the chemical etching process, in order to test its flexibility and for human body applications scenarios. The feeding technique for this antenna is the Coplanar Waveguide (CPW). The design and prototype of the antenna can be observed in Figure 3.3.

![Figure 3.3: Model and prototype studied in [13].](image)

The effects of bending were also tested for this antenna, since the purpose of this work was to achieve a wearable antenna to operate in the vicinity of the human body. It was applied the technique described before for bending the antenna, for simulation purpose, in $xx$ axis and $yy$ axis. The results regarding the difference between these two effects of bending demonstrates that the bending direction is relevant for the effects of bending.

The results were compared to the simulations in free space, to understand the difference between a smooth bending and a hard bending. The second scenario, of having a high bending degree shows a high impact of the antenna performance. This hard bending, observed in Figure 3.4 are far from reflecting the effects of bending when an antenna is placed in the human body.

![Figure 3.4: Antenna from [13] bent in $xx$ axis and $yy$ axis.](image)

Regarding the difference of bending in different directions, the results of return loss for simulation in free space, smooth bending and hard bending were tested are represented in Figure 3.5.
Kapton® is a flexible substrate capable of maintain an antenna performance, as already observed and further investigated in [14], where it was studied and concluded that a circular microstrip patch antenna could maintain its performance when testing the effects of bending. This substrate presents other advantages such as compatibility with several fabrication methods, high temperature resistance and a wide availability at low cost.

### 3.4 Conclusions

This chapter focused on analyzing the effects of bending and highlighting the importance of the substrate of flexible antennas. The technique for obtaining different bending degrees was studied and the respective results, regarding the return loss, were also presented.

In a second part of this chapter it was studied a flexible antenna prototype built upon Kapton®, which is the flexible substrate to be used in this work, in order to analyze the effects of bending. The direction of bending along different axes was tested, but this study considered high bending degrees, which are not so usual if we consider that the antenna will be placed inside a wallet.
4 DESIGN AND TEST OF A WEARABLE FLEXIBLE ANTENNA

In this chapter it will be presented the design process and construction of a wearable flexible antenna in free space, with the respective simulations and results of the prototype. The effects of bending will also be analyzed and presented.
4.1 Introduction

In the previous chapters several antennas have been studied within different bands of operations, different feeding techniques, different shapes and different materials for different applications. Since the prototype shape, substrate, feeding technique and band of operation were potentially selected from the previous studies, there are some several steps needed before the antenna test and construction. These steps demonstrates the roadmap of the prototype built to his work.

4.2 Antenna Design and Fabrication

For the process of designing and fabricate the antenna, some steps should be followed, as mentioned and described in [15], where five major steps can be considered for this process, are represented in Figure 4.1.

![Figure 4.1: Five major steps considered in design procedure of flexible wearable antenna.](image)

Regarding the first step, the material selection, it was studied and determined in chapter three to use Kapton® as substrate with a copper foil in one side of the substrate with CPW. In the second step it is necessary to characterize the material that will compose of the antenna. The characteristics of Kapton®, obtained from [16] for simulation purpose, along with a single metallization layer, a copper foil, are described in the tables 4.1 and 4.2 for 2.45 GHz. Both were properly configured in the CST Microwave Studio to obtain accurate results.
<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
<th>Electric conductivity [S/m]</th>
<th>Permittivity</th>
<th>Loss tangent</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton®</td>
<td>0.0508</td>
<td>-</td>
<td>3.4</td>
<td>0.07</td>
<td>1420</td>
</tr>
<tr>
<td>Copper foil</td>
<td>0.035</td>
<td>$5.8 \times 10^7$</td>
<td>-</td>
<td>-</td>
<td>8930</td>
</tr>
</tbody>
</table>

Table 4.1: Kapton® and copper foil characterization and properties in CST Microwave Studio.

With the material selected and the shape of circular disc monopole, also discussed previously, it is necessary to design the antenna in CST Microwave Studio. Several tests were made regarding the shape of the antenna in this phase. To test if circular disc was a good choice, it was also adopted and tested the shape in [17], as well as the shape studied in [6], for CPW, as shown in Figure 4.2. Both simulations for the Return Loss $|S_{11}|$ were compared with the results of simple circular disc chosen for prototype.

![Figure 4.2: Three different models simulated for this work.](image_url)

All the simulations considered a SMA connector in order to obtain results that could be compared to real measurements. Two different SMA connectors were used in the simulations, being the selected one for measurements, since it was the one available in laboratory, represented in Figure 4.3.

![Figure 4.3: SMA connector model used in CST Microwave Studio.](image_url)
Regarding the characterization of the materials which compose the SMA connector, it was also necessary to configure in CST Microwave Studio, as identified in Table 4.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
<th>Loss tangent</th>
<th>Electric conductivity [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>-</td>
<td>-</td>
<td>$5.8 \times 10^7$</td>
</tr>
<tr>
<td>Nickel</td>
<td>-</td>
<td>-</td>
<td>$1.4 \times 10^7$</td>
</tr>
<tr>
<td>Teflon</td>
<td>2.1</td>
<td>0.0001</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2: SMA connector characterization in CST Microwave Studio.

The results for the return loss, regarding the three different shapes, are presented in Figure 4.4 and it is possible to observe that the circular disc monopole is still a better option for the ISM band taking also in consideration the simplicity in fabrication process. Since the results regarding bandwidth and radiation patterns were also more than satisfactory for the circular disc, comparing with the two previous shapes, this was determined as the final shape for this work.

![Figure 4.4: Return loss simulation curves for the three models designed.](image)

In order to achieve an optimization in the parameters of the antenna, several simulations were performed to compare which are the optimal parameters for this prototype.

The main parameters that affects the return loss of the antenna, already studied in Chapter 2, are the line width, the gap between line and ground and the radius of the circular disc.

The results for different simulations, changing those parameters - line width, the gap and the radius - can be found in Figure 4.5, 4.6 and 4.7, respectively.
To ensure that the dimensions of the antenna were properly configured to a CPW impedance of 50 Ω, the tool in [18] was used. The final geometry of the antenna can be observed in Figure 4.8 and the respective dimensions in table 4.3.
Figure 4.8: Characterization of the circular disc monopole used in this work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>width of the substrate</td>
<td>55.00</td>
</tr>
<tr>
<td>$L$</td>
<td>length of the substrate</td>
<td>50.00</td>
</tr>
<tr>
<td>$W_g$</td>
<td>width of the ground</td>
<td>22.18</td>
</tr>
<tr>
<td>$L_g$</td>
<td>length of the ground</td>
<td>19.00</td>
</tr>
<tr>
<td>$w_f$</td>
<td>line width</td>
<td>8.00</td>
</tr>
<tr>
<td>$g$</td>
<td>gap between feeding line and ground</td>
<td>0.27</td>
</tr>
<tr>
<td>$h$</td>
<td>distance between circle and ground</td>
<td>1.50</td>
</tr>
<tr>
<td>$r$</td>
<td>circle radius</td>
<td>13.00</td>
</tr>
</tbody>
</table>

Table 4.3: Dimensions of the circular disc monopole used in this work.

To advance to the fourth step in the process, the antenna fabrication, it is necessary to understand the different types of fabrication processes. In [19] it is possible to list the advantages and disadvantages of each process, being the select one the chemical etching, illustrated in Figure 4.9. This process is accompanied by photolithography to build a mask and etchants to remove the selected area through a corrosive process.

Figure 4.9: Chemical etching process illustration.
The mask of the antenna, designed in AutoCAD, as well as the prototype at the end stage of the fabrication process are shown in Figure 4.10.

![Figure 4.10: Mask and prototype of the circular disc monopole.](image)

The fifth and final step would be the measurements of the prototype built, which will be analyzed and compared with the simulations, in free space and the effects of bending in free space.

### 4.3 Test of the Prototype Antenna in Free Space

The first simulation of the designed antenna was performed in free space, with no effects of bending, neither inside a wallet nor in the vicinity of the human body, since there it was necessary to optimize the antenna design.

In order to obtain a characterization of the antenna the simulations performed and analyzed in CST Microwave Studio were the Return Loss $|S_{11}|$, Bandwidth and Radiation Pattern.

In order to demonstrate how the geometry affects the RF characteristics of the antenna, the current distribution on its surface, at 2.45 GHz frequency is depicted in Figure 4.11.

As observed, the current distribution is mostly concentrated at the top of ground plane, feeding line and radius patch. The concentration of current at the top of ground plane, near the radiating patch, acts as part of the radiating structure, concluding the importance of the distance of the ground to the feeding line and the distance of the ground to circle patch, determined by the radius of the circle, in the dimensioning of the antenna.

![Figure 4.11: Current distribution in circular disc monopole for 2.45 GHz.](image)
4.3.1 Return Loss, $|S_{11}|_{\text{dB}}$

The Return Loss, $|S_{11}|_{\text{dB}}$, is the parameter that relates the incident and reflected power of the antenna, due to its own mismatching and it is expressed by the following equation:

$$|S_{11}| = 10 \log_{10} \frac{P_R}{P_I}$$  \hspace{1cm} (4.1)

It is usually considered that an antenna is tuned in a frequency band when the reflected power is less than or equal to 10% of the incident power, $P_R \leq 0.1 \times P_I$. This means $|S_{11}|_{\text{dB}} \leq -10\text{dB}$. Another criterion, less demanding, often used in mobile terminals, corresponds to a ratio between reflected power and incident power less than or equal to 25%, i.e., $P_R \leq 0.25 \times P_I$, or, $|S_{11}|_{\text{dB}} \leq -6\text{dB}$

In Figure 4.12 it is possible to observe the curve of return loss in free space, where it is visible the location at ISM Band.

![Figure 4.12: Return loss for circular disc monopole in free space.](image)

The result for the return loss in free space regarding the circular disc monopole, shows a properly configuration of the antenna to operate in the ISM band, since the peak of the return loss factor is at 2.45 GHz.

In order to compare the simulation with measurements, the antenna prototype was measured in IST laboratory using a network analyzer Agilent E5071C. It was necessary to use graphite to isolate the RF cable that was connected to the connector. The results that compare the simulation of the return loss with the measurement of the return loss can be observed in Figure 4.13.

In this analysis it is possible to observe, despite the effects of return loss reduction in laboratory, that the ISM band is covered for the antenna prototype in free space.
4.3.2 Bandwidth

In order to analyze the bandwidth of the simulation and measurement it was applied the expression of the bandwidth, given by the following equation:

\[
BW_{0} = 200 \times \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}} + f_{\text{min}}}
\]

(4.2)

This is a function of the maximum and minimum values of the operating band of the antenna, i.e., \(f_{\text{min}}\) and \(f_{\text{max}}\) respectively. Therefore, the antenna is tuned in the required bands, as the \(|S_{11}|_{\text{dB}} < -10\text{dB}\) at those frequencies. Considering that criterion \((|S_{11}|_{\text{dB}} \leq -10\text{dB})\), at the simulated frequencies, in free space, the percentage bandwidth is shown in Table 4.4.

<table>
<thead>
<tr>
<th>(f_{\text{min}}) [GHz]</th>
<th>(f_{\text{max}}) [GHz]</th>
<th>BW [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>2.090</td>
<td>3.365</td>
</tr>
<tr>
<td>Measured</td>
<td>2.340</td>
<td>3.475</td>
</tr>
</tbody>
</table>

Table 4.4: Bandwidth for simulation and measurement of circular disc monopole in free space.

Accordingly to the results observed in table 4.4 the antenna is tuned for the ISM band in both results – simulated and tested.
4.3.3 Simulated Radiation Pattern

The radiation patterns were analyzed using CST Microwave Studio, allowing to observe the two-dimensional and three-dimension spatial distribution radiated power. Since the radiation patterns can be represented by each component of the electric field, these are presented accordingly to $xz$ and $yz$ cut planes.

Figure 4.14: Three-dimensional radiation pattern for circular disc monopole in free space at 2.45 GHz.

The Figure 4.14 shows the three-dimensional radiation pattern (gain) for the frequency 2.45 GHz in order to observe the radiated power as function of the directivity of the antenna.

In the Figure 4.15 it possible to observe the bi-dimensional radiation patterns for the plans $xz$, $yz$ and $xy$. In order to obtain these radiation patterns, the variation of $Theta$ and $Phi$ are the key. For the plan $xz$ (horizontal) $Phi$ is defined as $0^\circ$ and $Theta$ is varying. For the plan $yz$ (vertical) it is applied the same method but with $Phi$ defined as $90^\circ$. Lastly for the representation of the plan $xy$ (vertical) it is $Phi$ that varies with $Theta$ defined for $90^\circ$.

Figure 4.15: Radiation patterns for circular disc monopole in free space at 2.45 GHz: (a) $xz$ plane; (b) $yz$ plane; (c) $xy$ plane
4.4 Prototype Antenna Bending Test

The first challenge that the antenna must overcome in terms of experimental results is the performance when bent, as already mentioned due to its utilization inside the wallet.

In Figure 4.16 we can see the image of the simulated antenna and the antenna prototype for the effects of bending. The degree of bending, described in chapter three, used for this simulation was 50 degree which is more than a wallet is bent in a normal situation. In this way it is possible to test the antenna to make sure that it will overcome the effects of bending a wallet in a common scenario.

![Figure 4.16: Bending the circular disc monopole model and prototype.](image)

4.4.1 Return Loss, $|S_{11}|_{dB}$

In first place it was possible to see a difference regarding the impact of the effects of bending the antenna, in CST Microwave Studio, when analyzing the return loss factor. In spite of the difference between the results of bending and in free space, in CST Microwave Studio, the experimental results were more similar to the simulated ones for the effects of bending. The return loss curve obtained in CST Microwave Studio for the effects of bending the antenna, 50°, along the yy axis, is presented in Figure 4.17.

![Figure 4.17: Return loss for bending the circular disc monopole.](image)
In the laboratorial environment it was also possible to test the return loss for the effects of bending the antenna prototype. The comparison between the return loss curves for simulation and measurement can be found in Figure 4.18.

Accordingly to the previous figure, we can observe the same shift, regarding return loss peak, from the experimental results to the simulated ones, but still operating efficiently in the ISM band.

### 4.4.2 Bandwidth

For the effects of bending it was also performed an analysis on the bandwidth to confirm that the ISM band is fully covered, since the tuning of the antenna, when bent, is covering the frequency range of 2.4 GHz to 2.5 GHz as shown in Table 4.5.

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{min}}$ [GHz]</th>
<th>$f_{\text{max}}$ [GHz]</th>
<th>BW [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>2.030</td>
<td>3.425</td>
<td>51.146</td>
</tr>
<tr>
<td>Measured</td>
<td>2.373</td>
<td>3.203</td>
<td>29.776</td>
</tr>
</tbody>
</table>

Table 4.5: Bandwidth for simulation and measurement of bending the circular disc monopole.

Since it was established a 50° for bending degree, it is possible to determine that smooth effects of bending for this antenna will not impact its performance, since the ISM band is still covered.
4.4.3 Simulated Radiation Pattern

The radiation pattern for the antenna when bending presents results very similar to the ones in free space, demonstrating the correct operation and radiation of the antenna for this scenario, as observed in figure 4.19.

Figure 4.19: Three-dimensional radiation pattern for bending the circular disc monopole at 2.45 GHz.

For the bi-dimensional radiation patterns in this scenario it is possible to see slightly differences regarding the radiation, in Figure 4.20, but still aligned with the conclusions that the antenna keeps its performance for this effects of bending.

Figure 4.20: Radiation patterns for bending the circular disc monopole at 2.45 GHz: (a) xz plane; (b) yz plane; (c) xy plane.

Despite the several options of bending, such as more bending degrees or a bending across the xx axis, the results were always aligned with the conclusion of the ISM Band being covered and similar radiation patterns.
4.5 Conclusion

In this chapter it was possible to observe and conclude that the antenna has fulfilled the requirements to operate within the ISM band in free space and also when bent. First it was compared the simulations results of the return loss factor and bandwidth with the measurement performed in laboratory for the prototype. The radiation pattern was also analyzed to conclude the major functionalities of the antenna prototype. In a second phase the simulation of the effects of bending the antenna was simulated and compared to the measurement of the prototype with similar effects of bending, in order to compare the return loss and bandwidth of the antenna in this environment. Since the results were successfully achieved for these two different measurements, according to the main objective of this work, the analysis can move forward to reach the final objective of the antenna prototype. As next steps, the simulations and measurements of the prototype can be performed in the vicinity of the human body and inside the wallet.
In this chapter it will be presented the final analysis for the objective of this work. The scenario of placing the antenna prototype inside a wallet and in the vicinity of the human body will be analyzed and presented.
5.1 Introduction

This chapter aims at the final objective of this work. For that purpose, tests and measurements of the prototype antenna inside a wallet and in the vicinity of human body are required. Since it was already observed and studied that the effects of bending the antenna keeps its performance, by having the ISM band covered, it is now necessary to confirm if it will keep the required performance when the antenna is inside a wallet. This chapter will present not only the results for the test and measurement of the antenna inside a wallet, but also in the vicinity of human body with respective conclusions.

5.2 Test of the Prototype Antenna inside a Wallet

To achieve the possibility of comparing simulation and measurements for this scenario, antenna inside a wallet, was necessary to configure a leather wallet in CST Microwave Studio, regarding its permittivity, loss tangent and density. As studied in [20] the characterization for leather material can be observed in Table 5.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
<th>Loss tangent</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leather</td>
<td>1.9</td>
<td>0.07</td>
<td>860</td>
</tr>
</tbody>
</table>

Table 5.1: Leather characterization in CST Microwave Studio.

It is important to highlight that the connector needed to stay outside the wallet for measurements and for a better comparison the same rational was applied in the simulations. The simulation was made with the antenna in one of the interior faces of the wallet. For the measurement result the antenna was placed in a similar position which corresponds to a common way of keeping the antenna inside a wallet. The design of the antennas inside the wallet and the prototype near the wallet used for measurements can be observed in Figure 5.1
The analysis included in the scope of this work are the same performed in chapter 4, i.e. the return loss factor and bandwidth are compared between simulations and measurements. For simulation it is also performed an analysis on the radiation pattern.

5.2.1 Return Loss, $|S_{11}|_{\text{dB}}$

It was expected to observe some consequences of the wallet on the antenna regarding the return loss curve. In simulation we can observe that effect, regarding a slightly shift of the frequency correspondent to the return loss peak, but not impacting the ISM operating frequency, i.e. it was not expected a disruptive consequence of the wallet in this analysis. The curve for the return loss can be observed in figure 5.2.

![Figure 5.2: Return loss simulation for antenna inside a wallet.](image)

The prototype was also measured inside a wallet, in IST laboratory, originating different results with the ones observed in the previous chapter. These results, are shown in figure 5.3.

![Figure 5.3: Return loss simulation and measurement for antenna prototype inside a wallet.](image)
This results lead to a positive conclusion regarding the performance of the prototype inside a wallet, as one can observe. The differences, already discussed in chapter four, between simulations and measurements are different for this scenario, since it was obtained a higher return loss curve for the measurement, being one possible reason the characterization of leather in simulations different from the actual characteristics of the wallet used for measurements.

### 5.2.2 Bandwidth

The bandwidth measured for the prototype and obtained in simulation are both covering the ISM band as observed in Table 5.2.

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{min}}$ [GHz]</th>
<th>$f_{\text{max}}$ [GHz]</th>
<th>$\text{BW}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>1.990</td>
<td>2.735</td>
<td>31.534</td>
</tr>
<tr>
<td>Measured</td>
<td>1.788</td>
<td>3.405</td>
<td>62.301</td>
</tr>
</tbody>
</table>

Table 5.2: Bandwidth for simulated and measured return loss.

In this scenario the measurement demonstrates a higher bandwidth, having almost the double of bandwidth percentage than the result for simulation. Nevertheless, both simulation and measurement achieve the requirements.

### 5.2.3 Simulated Radiation Pattern

The radiation pattern was also analyzed for this scenario to obtain the results three-dimensional and bi-dimensional for the scenario of having the prototype inside the wallet. In Figure 5.4 and 5.5 it is possible to see the radiation pattern of the antenna inside a wallet for 2.45 GHz.

![Figure 5.4: Three-dimensional radiation pattern for the antenna inside the wallet](image-url)
5.3 Test of the Prototype Antenna inside a Wallet in the vicinity of Human Body

The final simulation and measurement to be applied on the antenna and prototype is regarding a scenario where the antenna is placed inside a wallet in the vicinity of the human body, in order to obtain conclusions from the effects of the human body and test SAR values.

For the human body model in CST Microwave Studio it is possible to use either a voxel phantom, that has the shape and a large number of human tissues characterized, or a theoretical phantom, which is a simplified model of a human body with a characterization of the major human tissues that have impact on simulations, such as a simple shape rectangular, cylinder or elliptical, studied in [7].

Despite the level of detail that a voxel phantom can achieve, the simulation results obtained by a theoretical phantom can be accurate enough to compare with the required measurements. The voxel phantom, available in CST Microwave Studio and illustrated in figure 5.6, requires a high capacity processing due to its complexity.
For the purpose of this final analysis it was used a rectangular model, with the major human tissues characterized. The scenario of the antenna inside a wallet and in vicinity of the human body was designed in CST Microwave Studio and can be observed in Figure 5.7, as well as the prototype placed within this scenario details.

![Figure 5.7: Antenna design and prototype for scenario inside a wallet and in vicinity of human body](image)

In order to obtain the return loss curves and achieve accurate simulations, it is necessary to define the characteristics of the major human tissues that have impact on the simulation. These tissues are the bone, muscle, fat and skin. Their characterization, for 2.45 GHz frequency, are accordingly to previous studies about this scenario [21], [22] and can be observed in Table 5.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
<th>Conductivity [S/m]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>15.3</td>
<td>0.06</td>
<td>1850</td>
</tr>
<tr>
<td>Muscle</td>
<td>66.4</td>
<td>0.75</td>
<td>1040</td>
</tr>
<tr>
<td>Fat</td>
<td>6.1</td>
<td>0.04</td>
<td>1100</td>
</tr>
<tr>
<td>Skin</td>
<td>38.0</td>
<td>1.46</td>
<td>1100</td>
</tr>
</tbody>
</table>

Table 5.3: Human tissue characterization for simulation purpose.

Not only is important to characterize a proper human model to obtain accurate results when comparing with measurement, but also to predict the SAR values in order to conclude that the energy absorbed by the human body, for the antenna proposed in this work, is within the recommended values.
5.3.1 Return Loss, $|S_{11}|_{\text{dB}}$

The return loss simulation for this last scenario can now be analyzed since the wallet and the human body model are already properly configured. In Figure 5.8 it is possible to see the results for this simulation.

![Figure 5.8: Return loss simulation for antenna inside a wallet and vicinity of human body](image)

For the measurement, the wallet with the prototype inside was inserted in the pants’ pocket of a human male person. The results for measurement and comparison with the simulation obtained previously can be observed in Figure 5.9.

![Figure 5.9: Comparison of return loss simulation and measurement for antenna design and prototype inside a wallet](image)

From these results it is possible to analyze some of the effects of the human body on the prototype inside a wallet. Not only is possible to see the shift from the return loss peak between simulations and measurements, in line with the previous analysis, but also a new peak for the frequency 3.25 GHz due to the human body characteristics.
5.3.2 Bandwidth

The bandwidth analysis highlight the fact that for this measurement the ISM band is not covered, if we consider the -10 dB, as observed in Table 5.4.

<table>
<thead>
<tr>
<th></th>
<th>f_{\text{min}} [GHz]</th>
<th>f_{\text{max}} [GHz]</th>
<th>BW [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>2.015</td>
<td>2.590</td>
<td>24.97</td>
</tr>
<tr>
<td>Measured</td>
<td>1.505</td>
<td>2.225</td>
<td>38.61</td>
</tr>
</tbody>
</table>

Table 5.4: Bandwidth for simulated and measured return loss for antenna inside a wallet and in vicinity of the human body

Despite the results it is important to refer that we are analyzing a single measurement and considering the operation frequency below the -10 dB. For -6 dB this scenario it would also cover the ISM band.

5.3.3 Specific Absorption Rate

For the testing in the vicinity of the human body, not only is necessary to analyze the measurements regarding return loss, bandwidth, radiation patterns, but also it is vital to analyze one of the requirements of wearable antennas, which is the SAR.

<table>
<thead>
<tr>
<th>SAR</th>
<th>Maximum SAR [W/kg]</th>
<th>Total SAR [W/kg]</th>
<th>Average power [W/mm]</th>
<th>Maximum SAR at x/y/z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR (10g)</td>
<td>2.21</td>
<td>0.035</td>
<td>4.998 x 10^{-8}</td>
<td>0.31875 / 21.4945 / 21.8144</td>
</tr>
<tr>
<td>SAR (1g)</td>
<td>2.98</td>
<td>0.035</td>
<td>4.998 x 10^{-8}</td>
<td>-0.31875 / 22.9497 / 15.8589</td>
</tr>
</tbody>
</table>

Table 5.5: SAR values for antenna inside a wallet and in the vicinity of human body

The SAR values are inside the normalized parameters determined by the FCC, 4 W/kg, which was the final validation needed for this work analysis.

The results obtained in CST Microwave Studio regarding the SAR in the vicinity of the human model shape can be observed in Figure 5.10.
5.4 Conclusions

In this chapter the final objective for this work has been achieved, which was to analyze and study the performance of the prototype antenna chosen inside a wallet and in the vicinity of the human body. These analysis shows the return loss and bandwidth comparison between simulations and measurements, simulated radiation pattern for the antennas inside a wallet and the SAR calculated in the Microwave Studio. For the first scenario described, antenna inside a wallet, the results demonstrate that the antenna covers the ISM band for both simulation and measurement. In the second scenario, values were also aligned with all the analysis with the detail that the ISM band for the measurement was only obtained for return loss values below -6 dB. The values of SAR were also observed to be within the reference values of FCC. Regarding these conclusion, the objective of the work was achieved and properly analyzed.
6 CONCLUSIONS AND FUTURE WORK

In this chapter it is highlighted the main conclusion of this Thesis, summarizing the importance of the studies analyzed, the simulations performed and the outputs from the measurements of the antenna prototype. The future work related to the subject of this Thesis will also be discussed.
6.1 Main Conclusions

The main objective of this Thesis was to study and build an antenna prototype that could be used inside a wallet. A summary of the work done and how this objective was achieved is now presented.

As a first step, several articles were studied in order to have all the inputs necessary for the choice of the prototype antenna to be tested inside a wallet. The most relevant operations bands, UWB and ISM, were studied regarding flexible antennas and wearable antennas, with different shapes, different feeding techniques and different flexible substrates. Upon the decision of building a prototype to operate in the ISM band with a polyimide film, Kapton®, as the flexible substrate and a CPW feeding technique, three different shapes were designed in CST Microwave Studio, accordingly to [17], [6] and [10]. After comparing the simulations in CST Microwave Studio, it was decided to adopt the circular disc monopole shape. For this shape the return loss parameter was tested for different sizes of gap between feeding line and ground, weight of feeding gap and radius of the disc in order to obtain the best results and optimized dimensions.

In a second step, it was possible to focus on the analysis of the chosen prototype, built in IST laboratory through an etching chemical process, by starting the comparison of simulations with measurements. The prototype was measured in a network analyzer Agilent E5071C to obtain the results for the return loss parameter of four different scenarios – i) Measurements in free space; ii) Effects of bending; iii) Inside a wallet; iv) Inside a wallet in the vicinity of a human body.

For the first scenario, simulation and measurement in free space, it was possible to observe the differences between the simulations of an antenna designed in CST Microwave Studio and the measurements of a prototype measured in laboratory. Despite some differences in the return loss peak, it was possible to conclude the ISM band was covered in simulation and measurement results. The bandwidths obtained in simulation and measurement were compared to obtain the minimum and maximum values of bandwidth. It was also studied the simulated radiation pattern of the antenna, obtained through CST Microwave Studio. In a second scenario it was performed the same analysis, but for flexible testing, i.e. simulation of the effects of bending the antenna and measurement of the prototype antenna in similar scenario. It was also observed a slightly difference between the frequency of the return loss peak, but still covering the ISM band as desired.

For the third scenario, comparison between simulation and measurements, regarding the return loss parameter, were essential to conclude the feasibility of having a prototype antenna inside a wallet. The results were aligned with the first two scenarios, being the conclusion of this third scenario analysis, a confirmation that the ISM band was covered for the antenna designed and built, inside a wallet. Finally a test of the antenna inside a wallet in the vicinity of the human body was performed. The wallet with the antenna was placed inside a trousers’ pocket of a person, in order to evaluate the measurement of this scenario and compare with the simulation of the antenna in the vicinity of the human body. To achieve compliance with all the key factors that the antenna should comply with, SAR was calculated and it has been verified that the standard values were achieved.
6.2 Future Work

For future work of this Thesis, there are more tests that could be performed, which enters in detailed analysis such as durability, robustness, humidity and thermal tests, which are often not so relevant for antenna applications but increase the fundamentals of the prototype. Furthermore the prototype can be tested as part of an integration with an electronic device, to study different applications possibilities that an antenna inside a wallet can achieve. This new studies can be part of a recent subject of interest, called the Internet of Things (IoT), allowing an increase of interconnecting all objects and persons. This can be developed for several purposes, such as identity, tracking, safety, etc., in different industries [23]. The results obtained in this work also suggest the possibility of developing this antenna concept to applications such as flexible cell phones.

As a follow-up of the present work, other possible wallet antennas solutions, such as chip antennas, could be studied and tested. Although these solution could lead to smaller antennas, they are not as slim as the antenna prototype studied in this work, what could be undesired for practical applications.
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