Study and design of antennas for WLAN MIMO applications

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To the loving memory of my grandfather
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Last but not least, I am extremely grateful to all my family, specially my parents and brothers, for the help, support and love shared through these six years of university.
Resumo

Recentemente, as comunicações via Wireless, em especial, as redes WLAN têm vindo a ser cada vez mais utilizadas. As redes WLAN, usando a norma IEEE 802.11n tornam capaz uma maior capacidade de transporte de dados, bem como uma maior velocidade da comunicação. Para atingir estas exigências, os sistemas MIMO apresentam-se como uma boa solução. Para comunicações a curto alcance, devido ao seu custo reduzido e facilidade de fabrico, as antenas impressas são bastante procuradas face a estas necessidades.

Neste trabalho são apresentadas várias antenas MIMO de banda dupla, explorando diversidade espacial e de polarização, impressa sobre o substrato Rogers® rt/duroid 5880 com alimentação por guia de onda coplanar sintonizada para as frequências de 2.45 e 5.8GHz da banda Industrial, Científica e Médica (ISM). As estruturas foram simuladas em espaço livre (parâmetro-S, diagramas de radiação, coeficiente de correlação e ganho de diversidade). Posteriormente foi escolhida a antena de dois elementos que apresentou melhor desempenho e, juntamente com a estrutura de quatro elementos, foi fabricada. Foi analisado o desempenho das duas antenas através dos coeficientes de reflexão e transmissão medidos em laboratório.

Os resultados obtidos ficaram aquém do esperado a nível de ressonância das antenas, mas satisfatórios a nível de desacoplamento.

**Palavras-chave:** WLAN; Antenas MIMO; Diversidade espacial; Diversidade de polarização; Antenas de banda-dupla; Rogers® rt/duroid 5880; guia de onda coplanar (CPW); banda Industrial, Científica e Médica (ISM); Parâmetro-S; Coeficiente de correlação; Ganhoo de diversidade.
Abstract

Recently, the use of wireless communications and especially WLAN networks has been growing. WLAN networks that use the IEEE 802.11n standard have a greater capacity for data transport as well as a higher communication speed.

To achieve these requirements, MIMO systems present an adequate solution. Due to their reduced cost and straightforward manufacturing, printed antennas are in high demand for use in short range communications.

In this work, various printed double band MIMO antennas are presented, exploring spatial and polarization diversity, using the Rogers® rt/duroid 5880 substrate, fed by a coplanar waveguide, tuned to the frequencies of 2.45 and 5.8 GHz, from the Industrial, Scientific and Medical band (ISM).

The structures were simulated in free space (S-parameter, radiation diagrams, correlation coefficient and diversity gain). Subsequently, the two element antenna that presented the best performance was chosen, and it was manufactured along with the four element antenna.

The performance of both antennas was analysed using the reflection and transmission coefficient measured in the laboratory.

The obtained results were expected to be better in terms of the resonance of the antennas, however they were satisfactory in terms of the uncoupling.

Keywords: WLAN; MIMO antennas; Polarization diversity; Spatial diversity, Dual-band antennas; Rogers® rt/duroid 5880; Co-planar waveguide (CPW), Industrial, Scientific and Medical band (ISM); S-parameter; Correlation Coefficient; Diversity gain.
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Nomenclature

AP     Access Point
CDM    Circular Disk Monopole
CPW    Co-Planar Waveguide
FCC    Federal Communications Commission
HF     High Frequency
ISM    Industrial, Scientific and Medical radio frequency band
LF     Low Frequency
LTE    Long Term Evolution
MIMO   Multiple Input Multiple Output
MISO   Single Input Single Output
OFDM   Orthogonal Frequency Division Multiplexing
PM     Planar Monopole
RF     Radio Frequency
RFID   Radio Frequency Identification Device
SIMO   Single Input Multiple Output
SISO   Single Input Single Output
SNR    Signal-to-Noise Ratio
UHF    Ultra High Frequency
UWB    Ultra-Wide Bandwidth
VNA    Virtual Network Analyzer
WAN    Wide Area Network
Wi-Fi  Wireless Fidelity
WiMAX  Worldwide Interoperability for Microwave Access

WLAN  Wireless Local Area Network

WPAN  Wireless Personal Area Network

**Greek symbols**

\( \eta \)  \quad \text{Antenna efficiency.}

\( \lambda \)  \quad \text{Wavelength.}

\( \rho_c \)  \quad \text{Correlation coefficient}
Chapter 1

Introduction

1.1 Motivation

Wireless communications have been assumed a form of communication able to replace wire topology. In recent years, Bluetooth, Wi-Fi (IEEE 802.11), UWB registered a considerable level of growth, with a range of applications in everyday life.

All wireless local networks (WLANs) are based upon the IEEE 802.11 standard for WLANs, commonly called as Wi-Fi. Almost all today’s mobile devices use this technology. There are a range of standards within 802.11, which are denoted by a letter suffix. With the improved performance offered by 802.11n, the standard soon became widespread with many products offered for its use. The idea behind this standard was that it would be able to provide a much better performance and increase the link’s speed.

To achieve the desired fulfillment, a number of new features have been incorporated into IEEE standard to enable a higher quality. As such, in order to be able to carry very high data rates, 802.11n has utilised MIMO systems. The radio electric spectrum has become one of the most valuable goods for telecommunication operators and entities and MIMO technology ensures the maximum use of the available bandwidth. This method allows the multiplication of the capacity of a radio link using multiple transmit and receive antennas to explore the multipath propagation. Using different strategies such as spatial multiplexing, different types of diversity (time, frequency, space) and the required information coding, these goals can be achieved (as is shown in [1, 2]).

In order to achieve these goals, to obtain an effective MIMO system, it is necessary to have enough uncorrelated antennas at the beginning and end of the link.

In addition to the conventional antenna parameters, such as gain, radiation pattern and reflection coefficients, new parameters and aspects have to be considered in the design of MIMO systems, such as the mutual coupling and correlation between antennas.

Facing these challenges, printed antennas are assumed to be the best choice for MIMO systems, due to its low-cost, easy fabrication and small dimensions.

The work presented in this thesis is to study and design solutions that meet the above scrutinized...
challenges. There will be an explanation of the different works that have been elaborated with similar objectives, which were the basis for the design of the developed prototypes.

1.2 Thesis Objectives

The study of printed antennas for MIMO applications is the prime objective of this work, since there is a growing pursuit to provide the enhancement of the link’s data capacity and speed.

This dissertation aims at proposing antennas that perform as dual-band antennas (operating at 2.45 and 5.8GHz), fed by CPW technique and utilising multiple radiating elements.

The design and the free space simulations of the presented structures are performed using CST Microwave Studio software. The intention is to enhance the antenna's gain using multi-element structures and to isolate them as much as possible. The radiation pattern of the most relevant structures will be discussed.

After manufacturing the antennas, the S-parameters will be measured and the antennas’ performance will be analysed and discussed.
1.3 Thesis Organization

An overview of the most relevant wireless communications in printed antennas scope is discussed in chapter two, as well as a brief presentation on the evolution of MIMO systems and their general features.

The state of the art of printed antennas for MIMO applications is presented in chapter three. The papers referenced were an inspiration for the design of the structures shown in the following chapters.

In the fourth chapter, the whole design and the simulation process is presented. Antenna geometry, reflection and transmission coefficient, operation band, correlation coefficient, diversity gain and radiation pattern are presented in order to describe the antennas’ performance.

In the fifth chapter the measurements made (S-parameter) on the laboratory are presented and discussed.

Finally, in the sixth chapter, the main conclusions of the present work are addressed and some indications for future work are also pointed out.
Chapter 2

Overview of wireless communications and MIMO systems

2.1 Introduction

In recent years, wireless communication systems have increased rapidly. In high-bit-rate wireless communication for reduced multipath fading and increased capacity, multiple-input–multiple-output (MIMO) systems are suitable. The MIMO antenna array should have compact structure, high radiation efficiency, low envelope correlation, and high isolation between the signal ports. To achieve maximum channel capacity the array is also required to have high gain and wide lobe pattern.

Wireless communication systems have gone from different generations from SISO systems to MIMO systems. High data transmission rates are essential for telecommunication services. At the user end the capacity determines the quality of the communication systems.

In order to provide a good quality service for the users, an intensive research has been made on an attempt to increase data rate, transmission power and bandwidth required and to reduce error probability and implementation of the proposed system.

Facing these challenges, new levels of processing were needed to allow some of the features of spatial multiplexing as well as to use gain enhancement provided by diversity techniques.

This chapter aims at comparing the different RF wireless communication systems like SISO, MISO, SIMO and MIMO systems.
2.2 Wireless Technologies

Wireless communication is the transfer of information (data) between two points (transmitter and receiver) using electromagnetic waves, completely free from wires. Link distances can be short, for instance in an indoor environment, or long (thousands of kilometers), for deep-space radio communications.

This type of communication can be via radiofrequency, microwave (for long-range directional antennas, or short-range communications), or infrared (short-range). These systems are applied on point-to-point communications, point-to-multipoint communications, broadcasting and other wireless networks.

This work aims to explore short-range wireless communications. For that reason RFID, Bluetooth, WLAN and UWB are interesting technologies to be reported. Emphasis is given to the analysis of WLAN and UWB due to being technologies that are available for the construction of the prototype described in the next chapters.

On the following subsections an overview on wireless technologies (that are suitable to be utilised by printed antennas for MIMO applications) will be presented:

2.2.1 RFID

Radio Frequency Identification (RFID) is used to set the automatic identification of objects or people through the storage and retrieval of data when exposed to electromagnetic waves. These waves are then sent to an integrated compatible radio frequencies circuit, called RFID tag, and consequently information data is read by an RFID reader [3].

This technology started to be used after the Second World War (invented in 1948), and has been used for commercial applications since the 1980s.

In order to establish the communication in an RFID system, the transfer of energy (coupling) between tag and reader in RFID systems is done in three different ways: capacitive, inductive and radiative. The way these components couple can determine the read range and frequency of the system (see table 2.1). Coupling techniques are defined below along with some frequently used terms in the industry relating to communication.

Close coupling can employ electric or magnetic coupling, depending on the reader and tag. Readers employed for close coupling using a magnetic field are able to communicate in between 0.1 and 1 cm.

Systems can use electric currents instead of magnetic field in order to couple, which is called capacitive coupling. This type of coupling is only effective on a distance range of 1-2 cm and it is used at Low frequency communications.

Inductive coupling relies on the magnetic field of the reader, which means that this coupling only occurs in the near-field, that is defined by the reader and it is from 1cm up to 1m. Inductive coupling is present in LF, HF and UHF applications. Some applications include access control applications and any UHF application with a read range under 1 meter of distance.

Using (radiative Coupling) backscatter to communicate between readers and tags is a communication method involving electromagnetic waves (those are sent through the air from the reader to the tag
antenna). This coupling type is used by most of UHF systems. This coupling type allows reader/tag communication from 1 to 4 meters.

<table>
<thead>
<tr>
<th>RF band</th>
<th>Frequency Band</th>
<th>Coupling</th>
<th>Reading Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>120-140 kHz</td>
<td>Inductive</td>
<td>10-20 cm</td>
</tr>
<tr>
<td>HF</td>
<td>13.56 MHz</td>
<td>Inductive</td>
<td>10-20 cm</td>
</tr>
<tr>
<td>UHF</td>
<td>869-928 MHz</td>
<td>Backscatter</td>
<td>3 m</td>
</tr>
<tr>
<td>Microwaves</td>
<td>2.45 and 5.8 GHz</td>
<td>Backscatter</td>
<td>3 m</td>
</tr>
</tbody>
</table>

Table 2.1: RFID operating frequencies

2.2.2 Bluetooth

Bluetooth is a standard developed by a group of electronics manufacturers that allows any sort of electronic equipment to make its own connections, without wires, cables or any direct action from a user.

Devices which use this technology avoid interfering with other systems. This technology communicates on a frequency of 2.45 GHz (ISM band), it uses very weak signals (1 mW). Bluetooth uses a technique called spread-spectrum frequency hopping that consists on using 79 individual, randomly chosen frequencies within a designated range, changing from one to another on a regular basis. In the case of Bluetooth, the transmitters change frequencies 1600 times every second.

There are three different classes of devices that specify the maximum theoretical range of transmitted power level and working distance: class 1, with a maximum power of 20dBm and maximum distance of 100m, Class 2 (4dBm and 10m) and class 3 (0 dBm to 1 m).

This technology is used in WPAN, based on IEEE 802.15 [4].

There are two types of connectivity: Piconet (a WPAN composed up to 8 Bluetooth devices, with a master device and the rest called slave) and Scatternet (two piconets linked by a common node).

The future of this technology is based on the development of the 4th version of Bluetooth, called Bluetooth Smart (decreasing energy consumption and improving distance range and bandwidth) [5].

2.2.3 UWB

Ultra wideband (UWB) technology, is a form of transmission that occupies a very wide bandwidth, typically from 3.1 GHz up to 10.6 GHz and enabling it to carry data rates of Gigabits per second [6], [7]. The fact that UWB transmissions have such a wide bandwidth means that they will cross the boundaries of many of the currently licensed carrier based transmissions. As such, one of the main challenges is for UWB transmission not to cause interference. However, the very high bandwidth used also allows the power spectral density to be very low, and the power limits on UWB are being strictly limited by the regulatory bodies. In many instances they are lower than the spurious emissions from electronic apparatus that has been certified.

To date the FCC in the USA has approved UWB, ultra wideband technology for indoor and short range outdoor communication, but with restrictions on the frequencies over which the transmission can...
spread as well as the power limits. This will enable the UWB transmissions to communicate successfully, but without affecting existing ‘narrowband’ transmissions.

To achieve these requirements the FCC has mandated that UWB, ultra wideband transmissions can legally operate in the range 3.1 GHz up to 10.6 GHz, at a limited transmit power of -41dBm/MHz. Additionally the transmissions must occupy a bandwidth of at least 500 MHz, as well as having a bandwidth of at least 20% of the centre frequency. To achieve this last requirement, a transmission with a centre frequency of 6 GHz, for example, must have a bandwidth of at least 1.2 GHz.

There is a wide number of applications for UWB technology. They range from data and voice communications through to radar and tagging. With the growing number of ways in which wireless technology can be used, the list is likely to grow.

Although much of the hype about ultra wideband UWB has been associated with commercial applications, the technology is equally suited for military applications (see table 2.2).

<table>
<thead>
<tr>
<th>Sector</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>High speed LAN / WAN</td>
</tr>
<tr>
<td></td>
<td>Avoidance radar</td>
</tr>
<tr>
<td></td>
<td>Altimeter</td>
</tr>
<tr>
<td></td>
<td>Tags for intelligent transport systems</td>
</tr>
<tr>
<td></td>
<td>Intrusion detection</td>
</tr>
<tr>
<td></td>
<td>Geolocation</td>
</tr>
<tr>
<td>Military</td>
<td>Radar;</td>
</tr>
<tr>
<td></td>
<td>Covert communications;</td>
</tr>
<tr>
<td></td>
<td>Intrusion detection;</td>
</tr>
<tr>
<td></td>
<td>Precision geo-location;</td>
</tr>
<tr>
<td></td>
<td>Data links;</td>
</tr>
</tbody>
</table>

Table 2.2: UWB applications

With the growing level of wireless communications, ultra wide band UWB offers significant advantages in many areas. One of the main attractions for WAN / LAN applications is the very high data rates that can be supported. With computer technology requiring ever increasing amounts of data to be transported, it is likely that standards such as 802.11 and others may not be suited to support the data speeds required in some applications. To overcome this problem where UWB may well become a major technology in the near future.

2.2.4 Wi-Fi

WiFi stands for Wireless Fidelity. It is based on the IEEE 802.11 family of standards and is primarily a local area networking (LAN) technology designed to provide in-building broadband coverage.

Current WiFi systems support a peak physical-layer data rate of 54 Mbps and typically provide indoor coverage over a distance up to 1000 m (see table 2.3).

WiFi has become the standard for last mile broadband connectivity in homes, offices, and public hotspot locations. Systems can typically provide a coverage range of only about 1,000 feet from the access point.
WiFi offers remarkably higher peak data rates than 3G systems do, mainly since it operates over a larger 20 MHz bandwidth, although WiFi systems are not designed to support high-speed mobility.

One significant advantage of WiFi over WiMAX and 3G is its wide availability of terminal devices. All of laptops and smart phones shipped today have a built-in WiFi interface. WiFi interfaces are also being built into a variety of devices, including personal data assistants (PDAs), cordless phones, cellular phones, cameras, and media players.

The IEEE 802.11 Wi-Fi/WLAN standards set the attributes for the different channels that may be used (see table 2.3). These attributes enable different Wi-Fi modules to talk to each other and effectively set up a WLAN [8].

WLAN is a wireless network that is able to connect two or more devices in a limited area. Every device that is connected to a WLAN is considered as a station, and it could be defined as an access point or a client. APs receive and transmit RF signals from devices that are capable of receiving transmitted signals, typically working as a router.

To ensure that WLAN solutions operate satisfactorily, parameters such as the RF signal centre frequencies, channel numbers and the bandwidths must all be set.

All stations that are able to communicate with each other are called Basic Service Sets (BSSs) and they can be independent (when two clients can communicate without using an AP, but cannot connect to any other BSS), called peer-to-peer network, or an infrastructure that is able to communicate with any other station but only on other BSS and using an AP.

<table>
<thead>
<tr>
<th>IEEE Standard</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Maximum Data Rate (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11</td>
<td>2.4</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>802.11a</td>
<td>5</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>802.11n</td>
<td>2.4, 5</td>
<td>20, 40</td>
<td>600</td>
</tr>
<tr>
<td>802.11ac</td>
<td>5</td>
<td>20, 40, 80, 160</td>
<td>6930</td>
</tr>
<tr>
<td>802.11ad</td>
<td>60000</td>
<td>2160</td>
<td>6760</td>
</tr>
</tbody>
</table>

Table 2.3: IEEE Standard for Wi-Fi operating band

The idea behind the IEEE 802.11n standard was that it would be able to provide much better performance and be able to keep pace with the rapidly growing speeds provided by technologies such as Ethernet.

To achieve this, a number of new features have been incorporated into the IEEE 802.11n standard to enable the higher performance, such as OFDM implementation (a form of transmission that uses a large number of close spaced carriers that are modulated with low data rate) and MIMO, in order to be able to carry very high data rates, often within an office or domestic environment [9].
2.3 MIMO systems

Refering to the radio link, there are different forms of antenna technology configuration concerning the multiplicity of inputs and outputs.

The simplest figuration on radio link system is defined as Single-Input-Single-Output (SISO), where both the transmitter and receiver operate with a single antenna, there is no diversity and no additional processing required. SISO systems are used in multiple systems such as Bluetooth, Wi-Fi, radio broadcasting and TV. However, these systems are limited on their performance. Rates above 1 Gbps rate can only be obtained by using wide input power and bandwidth. In addition, multipath is unavoidable using these systems and fading reveals to not be constant in time [10]. This causes several issues like losses and attenuation and also the reduction in data speed, packet loss and increased errors.

Exploiting different kinds of diversity, both on the receiver and transmitter terminals, two solutions have arised.

Single-Input-Multiple-Output (SIMO) systems, which apply spatial diversity on the receiver, is often used to combat effects of fading and interference. Despite being easy to implement, SIMO systems require processing in the receiver which may limit the performance in several applications as mobile communications (by size, cost and battery drain). Futhermore, the channel capacity on the link does not increase when applying this technology [11].

![Different methods to combine signals.](image)

To optimize the Signal-to-Noise-Ratio (SNR) on these systems, the signals provided from the transmitter can be associated in three different ways, known as Switched Diversity or Combining Selection (the system selects the strongest signal and switches from the different antenna elements), Maximum Ratio Combining (only the strongest received signals are summed and linearly combined) and Equal
Gain Combining (all the received signals are combined which will result on a higher combined output SNR comparing it to the signal from each antenna) [12, 13].

On the other hand, Multiple-Input-Single-Output (MISO) systems, also termed transmit diversity, take advantage specially on cellphone communications (in which less power is used and processing is required at the user end or receiver end). The same data is transmitted redundantly from several transmitter antennas. Then, the receiver gets the optimum signal and extracts the required data. The main benefit of this technology is that the multiple antennas and the redundancy coding and processing is shifted to the receiver, which helps to reduce the effects of multipath wave propagation, delay and packet loss. However, MISO systems particularly utilise time diversity, which doesn’t represent a good solution by not increasing the channel capacity and high data rates [14, 15].

Introducing more than one antenna at the receiver and transmitter, MIMO systems have emerged and they represent the most effective solution concerning channel robustness and throughput, despite showing high costs in additional processing and number of antennas used [16].

![Figure 2.2: Block diagram of a MIMO system utilizing spatial multiplexing, in [17]](image)

The initial work on MIMO systems focused on basic spatial diversity (the MIMO system technology was used to attenuate the degradation caused by multipath propagation). However, this technology started to use the multipath propagation as an advantage, turning the additional signal paths into what might effectively be considered as additional channels to carry additional data [17].

When affecting the channel link, multipath fading impacts the signal to noise ratio which will result in a higher the error rate. On MIMO systems, the concept of diversity is exploited in order to provide the receiver with different versions of the transmitted data (the probability of all these different signals types to be affected at the same time by the signal path is considerably reduced). There are different diversity modes used, providing several advantages, in order to help to improve link performance, reducing error rate such as time diversity (a message may be transmitted at different times, using different timeslots and channel coding), frequency diversity (using different frequencies, it may utilise different channels or technologies such as OFDM) and Space diversity (it uses several antennas located in different positions to combat multipath).

On the very first studies, the multiple paths taken by the transmitted message only served to introduce interference. By moving the antennas a small distance, these paths will change. MIMO systems uses these additional paths to provide additional robustness to the radio link by improving its performance. For this goal, Spatial diversity (in order to improve the reliability of the system concerning to the different
forms of fading) and Spatial Multiplexing (used to provide additional data capacity using the different paths to increase the link data capability) [18].

Using a multiple number of antennas, with MIMO wireless technology systems it is possible to transmit data with a substantial growth of the channel's capacity without contravening Shannon's law [19, 20].

![Figure 2.3: Average Capacity on a MIMO Rayleigh fading channel [21]](image)

For each transmitter/receiver pair of antennas added to the system, the average capacity of a MIMO Rayleigh fading channel increases linearly (see figure 2.3 and [21]), making this technique a huge step in Wireless Communications nowadays, enabling the use of the available bandwidth more effectively. In order to use MIMO spatial multiplexing, it is required to utilise coding techniques so that the correct data can reach the receiver. These coding techniques can be Space Time block codes, MIMO Alamouti coding and Differential space time block code [22].
Chapter 3

Antenna design for MIMO applications

3.1 Introduction

Electromagnetically printed antennas are developed to provide every wideband impedance characteristics. Many parameters optimize the impedance bandwidth of this antenna which has to be investigated. These antennas are built up for modern wideband wireless applications like mobile phones or Wireless LAN, Bluetooth, UWB and RFID technologies.

As mentioned in the previous chapter, MIMO systems perform best when they can answer to the issues related to antenna theory such as array configuration, radiation pattern, type of polarization and mutual coupling.

To find out the proper design and configuration of the MIMO antenna, it’s important to satisfy the requirements concerning its final wireless application.

However, it is acceptable to define some essential properties that must be confirmed to ensure a good performance and to operate in the best possible manner. These requirements must be taken into account to optimize the antenna performance. Nonetheless, these characteristics are not independent from each other.

A brief discussion follows:

- Size: The size (volume) of the antenna and its overall impact on the surrounding environment is extremely important for most wireless communication systems. Probably the biggest issue with utilizing small antennas for wireless communications is the reduction in efficiency.

- Efficiency: The greater the efficiency, the better the link budget.

- Bandwidth: The designed antenna must satisfy the bandwidth requirements for the wireless system. The gain bandwidth and return loss bandwidth (frequency range in which the return loss is better than -10dB) must be satisfied.

- Polarization: in order to reduce the multipath fading and probability of error and to increase the channel capacity.
- Power Handling: needed to define the materials required for the antenna to satisfy its application.

Considering these requirements and adding the need for low-cost solutions, printed antennas appear to be the best choice. However, by appearing in many forms, the best suited for a specific application may not be clear.

### 3.2 Printed Antennas

#### 3.2.1 Overview

Printed Antennas, in its most basic form, consist of a radiating patch on one side of a dielectric substrate which often have a ground plane on the back side.

Due to its low-cost, easy fabrication, and small dimensions, printed antennas are simple to integrate in mobile terminals.

For good performance, a thick dielectric substrate with a low dielectric permittivity is suitable by providing better efficiency and larger bandwidth. Although the antenna directivity is independent of the substrate thickness, the antenna efficiency and bandwidth performance depends on the dielectric permittivity of the substrate.

There are three main types of flat profile printed antennas as it is shown on the figure 3.1 ([23]).

![Printed Antenna Shapes](image)

(a) Travelling Wave Antennas  
(b) Patch Antennas  
(c) Printed Slot Antenna

Figure 3.1: Printed Antenna Shapes

All of these antenna types have a thin profile and are able to operate in more than a single frequency.
In addition to having a high performance, microstrip patch antennas have the easiest way of fabrication (can be manufactured in large quantities), support both linear and circular polarizations and are able to be produced in any kind of shape.

### 3.2.2 Printed patch antennas

Among patch antennas there are different types of feeding techniques for printed antennas, two of which stand out among others: Microstrip Line Feed, 3.2(a) (the microstrip line and ground plane, made of the same conductor material are placed on opposite sides, which may have an air gap between the ground plane and substrate) and Coplanar Waveguide (CPW), 3.2(b), (contains a single conductive metallic layer on the substrate that includes the radiator and ground plane).

![Microstrip Line](image1.png) ![Coplanar Waveguide (CPW)](image2.png)

(a) Microstrip Line  (b) Coplanar Waveguide (CPW)

Figure 3.2: Feeding Line Techniques

These topologies influence the antenna’s performance and the type of feed technique must be chosen according to its application. On the table 3.1 there are some differences that can be remarked between CPW and Microstrip line:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Microstrip Line</th>
<th>Coplanar Waveguide (CPW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Losses</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Coupling</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Design Flexibility</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Circuit Size</td>
<td>Large</td>
<td>Small</td>
</tr>
</tbody>
</table>

Table 3.1: Microstrip line and CPW feeding types

In [24, 25] two different antennas were designed in order to operate at 2.45 GHz frequency (ISM Band), on a FR4 substrate with $\varepsilon_r=4.6$ and thickness 1.6 mm), suitable for Body-Centric and wireless communications, respectively. Reference [25] exploits an Electromagnetic Band-Gap (EBG) in order to achieve desirable electromagnetic properties that cannot be observed in natural materials. In both cases, the feeding technique used is a Microstrip Line.

Circular Disc Monopole (CDM) with a a CPW feeding (using FR4 substrate, as well) with 50 Ohm impedance matched with the coaxial cable and two notches cut on the circular disk patch (used to increased the reflection coefficient at lower frequencies), as it shows [26], reveals to be an interesting solution for UWB applications.

A dual-band transparent antenna for ISM applications is studied in [27]. Figure 3.3 shows the antenna...
design that consists of a circular radiating patch fed with a 50 Ohm CPW feeding and uses a transparent thin film material (AgHT-4) as substrate, with an overall size of $60 \times 60 \times 2.075\text{mm}^3$.

![Antenna design mask](image)

Figure 3.3: Antenna design mask [26]

On the circular patch, different slots were cut and most of the surface current is distributed on the U-slot and line slot, at 2.45GHz, figure 3.4(a), and 5.8GHz, figure 3.4(b).

Figure 3.5 shows that, without slots, the antenna doesn’t resonate when there are no slots on the patch. However, when the U-slot is introduced, there is a resonating frequency at 2.45GHz (figure 3.4(a)). The line slot has produced the resonating frequency at 5.8GHz (figure 3.4(b)).

![Surface Current at 2.45 and 5.8GHz](image)

Figure 3.4: Surface Current at 2.45 and 5.8GHz [26]
Despite being favourable, printed antennas present lower gain (about 6dB), excitation of surface waves, low efficiency (due to dielectric and conductor losses) and low power handling capacity. However, these obstacles can be overcome using MIMO techniques.

### 3.3 MIMO antenna solutions

In [28], several considerations concerning MIMO Antenna design are established in order to optimize aspects such as array configuration, radiation pattern, type of polarization and mutual coupling. This paper suggests different concepts and solutions for MIMO systems such as Antenna array configuration and reconfigurable antennas.

Antenna array or phased array system consist on a set of patch antennas with different layouts. The array topology is decided in order to maximize capacity and minimize error rate. In MIMO arrays, the correlation between the multiple signals must be as least as possible to counteract the scenario of degradation in channel capacity. Gain enhancement can be achieved by using several diversity strategies:

- **Spatial Diversity**: different elements are spaced with optimum distance to increase the number of channels in the link. In this technique, the smaller the distance, the more the mutual coupling between antennas, which result in a reduction of the channel capacity.

- **Polarization Diversity**: elements in the array are fed with differently polarized signals.

- **Pattern Diversity**: the signals with different angles are given to each one of the antennas present in the array.

MIMO antenna systems can be used in order to achieve different goals such as increasing the overall gain, cancelling out the interference from a particular set of directions and maximizing the Signal to Interference Pulse Noise Ratio (SINR) - to establish the maximum limit concerning to channel capacity.
3.3.1 State of the art

Several investigations on printed antennas suitable for MIMO applications have been reported.

An E-shaped triband printed monopole antenna suitable for WLAN applications is proposed in [29] (figure 3.6(a)). The dimension of the rectangular monopole is near $\lambda/4$, and two L-shaped patches are added resulting in an E-shaped antenna, leading to a single frequency band antenna. According to the author an U-shaped current path is created with odd multiples of $\lambda/4$ length, introducing an extra resonant mode to be added to the initial E-shaped antenna structure. The third resonant mode was achieved by splitting the slot in two, adding an extra smaller U-shaped current path 3.6(b) and resulting in a triband frequency response within the WLAN range.

A substrate with a permittivity $\epsilon_r = 2.2$, thickness of 0.8mm was used and the overall size of the antenna was $35 \times 35mm^2$ for the triband behaviour at 2.4, 5.4 and 5.8GHz.

The presence of the slots does not influence the lower frequency, while the different slots and its width tunes the frequency of the second and third resonancy band 3.6(c).

![Monopole design](image1)
![Surface Current distribution with double slot](image2)
![Simulated(S) and measured(M) return loss of E-shaped antenna](image3)

Figure 3.6: Design, surface current and reflection coefficient in [28]

The author has concluded that the element could be arrayed for a MIMO purposes.
Based on the five possible layout topologies to arrange the antenna, the author presents the simulated S-parameter, figure 3.7. The spacing between array elements is set at 10 mm (almost $\lambda/10$ of the lowest resonance frequency). In every attempt, there are changes concerned to the position, pattern and polarization of the elements that leads to different results. Figures 3.7(d) and 3.7(e) show a lower mutual coupling compared to the structures which use only spatial diversity (with parallel elements).

The author finally concludes that the proposed antenna array shown on 3.7(e) is a possible candidate for use in MIMO applications due to its low mutual coupling (as it is shown on the figure 3.8(a) that presents the measured S-parameter), low envelope correlation (3.8(b)) and good omnidirectional radiation patterns.

![Figure 3.7: Simulated S-parameter and different configurations of MIMO E-shaped element array studied in [28] (S11 on black, S12 on red and S22 on blue)](image)

It is discussed in [30] an approach that exploits the structure and design optimization of a MIMO antenna into two separated steps which are the design of a single radiator element and its incorporation into the MIMO system. An array system with two UWB monopole antennas placed perpendicularly has
been designed, taking special attention to its isolation.

MIMO arrays can be suitable for UWB applications, as it is reported on [31]. The author proposes a UWB MIMO antenna, with a bandwidth from 3.1 to 10.6 GHz, with a compact size of $26 \times 40$ composed by two planar-monopole (PM) elements with 50 Ohm microstrip-fed placed perpendicularly to each other, in order to provide good isolation between the two input ports, shown on 3.9(a). Antennas have been designed on RO4350B substrate with a 0.8mm thickness, a permittivity of 3.5 and a loss tangent of 0.004.

For better matching at high frequencies, a small rectangular slot was cut on the upper edge of the ground plane.

To increase isolation and impedance bandwidth, two long ground stubs were introduced, placed in parallel with the respective PM, figure 3.9(b).

These structures were placed in order to satisfy the requirements implicated by the UWB operation (stub 1 generated a resonance at 3.5GHz for S11 and stub 2 for 4 GHz on S22). The short ground strip is also placed in order to reduce the mutual coupling between elements and to enhance the isolation. Results have shown that the MIMO antenna proposed has achieved an envelope correlation coefficient of less than 0.2 across the UWB bandwidth range (see figure 3.10).

In order to mitigate the effects of multipath fading to reduce the error probability, different radiation patterns were employed, where two PMs were placed perpendicularly to each other. Hence, two different radiation patterns, as it is noted in [31], to receive signals from different directions, obtaining pattern diversity.
In [32] a similar approach is taken, a UWB MIMO band-notched is proposed, with an overall size even smaller than the antenna presented in [31] (printed on the same substrate). The antenna is composed by two square monopole elements, a T-shaped ground stub with a vertical slot cut to reduce mutual coupling (and increase isolation) and two strips on the ground plane to create a notched resonant frequency from 5.15 to 5.85 GHz to suppress interference in the WLAN. The results presented show a good envelope correlation coefficient (lower than 0.06) through the UWB. This MIMO antenna was then installed on a printed circuit board (PCB) with a standard size, with an USB connector and device housing which didn’t influence the antenna performance.

Another example of UWB technology in MIMO systems (in this case, for on-body operation) is studied in [33], where two antennas with spatial and polarization diversity were built in order to measure its performance. The basic element consists on ring monopole printed on a low loss substrate RO3003 (0.75mm thick and $\epsilon_r = 3$) fed by a microstrip line of 50 Ohm. The antenna was also studied with CPW feeding technique and with an addiction of a filter, proving to be a better solution.

Facing the huge demand on data requirement at any time and place in wireless communications, multipath fading is a special issue that is taken into account and there are several strategies in order
to increase the isolation between different system elements such as stubs, in order to not increase too much the size of the antenna. In [34] an antenna has been designed for 2.4/5.2/5.8 GHz WLAN and 2.5/3.5/5.5 GHz WiMAX applications that consists of two back-to-back monopole antennas, using a strategy to reduce the mutual coupling between two ports at the lower frequency band, introducing a T-shaped stub, where two rectangular slots are cut from the ground. According to the author, the proposed antenna system is suitable for portable MIMO/diversity applications.

A different approach is made in [35], where a compact microstrip patch antenna with four ports has been designed and implemented. The presented antenna consists of two patches operating at LTE frequencies (1.8, 2, 2.6 GHz) and two patches operating at WLAN frequency (2.4GHz), fabricated on a FR4 substrate ($\epsilon_r = 4.4$ and thickness of 1.6mm). The patches are placed parallel to each other and printed with different orientations in order to achieve pattern diversity and low correlation coefficient.

In [36] a directional shorted four-port patch antenna is introduced, fed with vertical probes which can operate either in dual linear and circular polarization modes in order to increase system capacity. To achieve circular polarization, the currents distributed by the four shorted patches are fed in phase opposition (the proposed antenna radiates in left hand circular polarization), while dual polarization is introduced by exciting each pair with the same magnitude in anti-phase. The same concept is introduced on [37] structured with two printed F antennas on the top layer of a FR4 PCB with a rectangular ground plane underneath and a pair of quarter wavelength slot antennas inserted diagonally on the back side of the PCB. The quarter wave length slots are placed to achieve better isolation between the F antennas and to use as a radiator, increasing the resonance at the desired frequency.

Another report was made to explore different configurations of a dual-element symmetric planar monopole used to form a MIMO antenna system for LTE2300 (Asia and Africa) and ISM operations, on [38], as is it shown on 3.11. The system is printed on a FR4 substrate (1.6mm thick, $\epsilon_r = 4.4$).
The author has attempted different configurations using the two monopoles, which are spaced with a 7.8mm distance. In figure 3.12(a), the elements are introduced in the same direction (another configuration was tried, increasing the distance between the elements, but the results were still not satisfactory). However, the isolation had been deteriorated (fig. 3.12(b)) comparing to the proposed system, fig. 3.11(b) and 3.11(c). These results allow the author to conclude that the isolation is affected not only by the distance between elements, but also by the rotation of the current on the radiation patch.

An arrangement was then shown with the two elements placed orthogonally (fig. 3.12(c)) resulting in a higher isolation (fig. 3.12(d)) but the total size of the system was higher than the final choice (the proposed system has been decided taking into account the space and system performance).

Finally, an eight-element MIMO antenna system was built showing quite reasonable results.
Figure 3.12: Geometry and S-parameters simulated of the orthogonal and parallel arrangement systems in [38]
Chapter 4

Study and design of dual-band MIMO antennas for WLAN applications

4.1 Introduction

This chapter aims at explaining all the developed processes involving the design and simulation of the studied antennas.

The design method started by choosing the materials used as well as the feeding technique. Then the operating frequencies and the patch shape were chosen. Finally, the component’s length was optimized in order to obtain the resonance at the intended frequencies, and there was also a readjustment of the antenna’s overall size, to make it as small as possible.

Firstly, a model of the simulated reference element will be presented as well as an explanation of the choices made in its construction. Then the simulated MIMO structures are presented. Initially, two element structures are shown utilising various types of diversity and showing various different configurations in order to choose the final structure to be manufactured.

Subsequently, a structure composed of 4 elements will be introduced in order to obtain omnidirectional radiation pattern.

For all the structures presented there is an analysis of their performance, both in terms of S-parameter, correlation coefficient and diversity gains. For the most relevant structures, a relative analysis of the radiation pattern is also performed.

In this chapter there will be an analysis of all the points related to the models simulated by CST Microwave Studio® software.
4.2 Geometry and simulations of the reference element

The basic element that was designed in order to build the proposed MIMO system is presented in figure 4.1. To obtain the corresponding designed dimensions, several parameters such as the slot’s length and the spacing between the strip line and the ground plane had to be adjusted. In order to tune the frequencies for the required application and increase the resonance on these frequencies (2.45GHz and 5.8GHz), multiple parameter sweeps were made.

The element is composed by a circular radiating patch with a U-slot that ensures resonance on the desired frequencies. A CPW feeding technique was used in order to reduce the circuit size and coupling and increase the design flexibility, as suggested on [39], [40],[41],[42].
Taking into account the available options at the DEEC prototyping room, the substrate chosen was Rogers® rt/duroid 5880.

Some physical and chemical features of the substrate are presented in table 4.1:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>1.575</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>0.0004</td>
</tr>
<tr>
<td>Dielectric Permittivity</td>
<td>2.20</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-50 to 150 °C</td>
</tr>
</tbody>
</table>

Table 4.1: Rogers® 5880 Properties

To describe and analyse an antenna’s behaviour as well as its operating band, the reflection coefficient is most commonly used. The absolute value of this parameter relates to antenna impedance matching and is defined by the ratio between the reflected power, $P_r$, to the antenna’s incident power, $P_i$:

$$|S_{11}| = 10 \log_{10} \frac{P_r}{P_i}$$

(4.1)

To determine the operating band of an antenna there is one condition that must be satisfied:

$$\begin{cases} 
|S_{11}| \leq -10dB \\
P_r \leq P_i \times 0.1
\end{cases}$$

(4.2)

Observing figure 4.2, it can be concluded that the described element has two resonant frequency bands at 2.45 GHz and 5.8 GHz (ISM operations), being described as a dual-band antenna.

![Figure 4.2: S-parameter for the reference element](image)

The results observed, enables to understand the influence of the parameters in order to optimize the performance of the element of reference.
In figure 4.3(a), it can be concluded that the U-slot presented on the patch ensures the resonance on the higher frequency (5.8GHz) and increases it on the lower frequency (2.45GHz) as well. Figure 4.3(c) shows the variation of the slot’s length.

In figure 4.3(b), the variation of the gap’s length between the feeding line and the ground plane of the coplanar waveguide feed is shown. This parameter ensures resonance at the lower frequency and its value was initially chosen using the macros calculator available on the simulator. The optimum value was approximately 0.074 mm but due to limitations of the manufacturing process, the value chosen was 0.12 mm. Despite that, this value is correspondent to the 50 Ohm impedance of the SMA Connector that was used (4.6).

Figure 4.4 shows the surface currents at the resonant frequencies. The lowest values are represented in green while the best are represented in red. It is noticed that the currents are not noticed on
the upper part of the radiating circular patch and for that reason it was possible to cut this area in order to reduce the antenna size so that it could become more compact.

Figure 4.4: Surface current of the element of reference

In order to optimize the element performance, the ground plane was cut. As it is seen in figure 4.5, this cut improved the resonance at the lower frequency, adjusting it for the desired 2.45 GHz.
(a) Element's representation without the ground plane cut

(b) Comparison between element's performance with and without the ground plane cut

Figure 4.5: Element representation and S-parameter without the cut made on the ground plane

Figure 4.6: Geometry of the basic element with SMA connector.
Radiation patterns are functions or graphic representations of the antenna’s spatial radiation properties. A spherical coordinate system (figure 4.7) is used to make this representation and the planes that can represent the radiation pattern are the following:

- Horizontal Plane (XZ): $\Phi = 0^\circ$ varying with $\theta$
- Vertical Plane (YZ): $\Phi = 90^\circ$ varying with $\theta$
- Horizontal Plane (XY): $\theta = 90^\circ$ varying with $\Phi$

Figure 4.7: Coordinate system used to represent the radiation pattern
In the following figures a polar representation of the radiation pattern of the element of reference at 2.45 and 5.8GHz are shown:

Figure 4.8: Radiation pattern for 2.45GHz of the element of reference in different planes
Figure 4.9: Radiation pattern for 5.8GHz of the element of reference in different planes
4.3 Multi-element structure

This section studies the influence of diversity gain (spacial and polarization). Significant SNR improvement and added gain is expected when using diversity systems, which are evaluated by three main parameters: correlation coefficient, diversity gain and antenna efficiency (that is not included in this work).

4.3.1 Signal port correlation coefficient

Diversity gain is measured based on the signal ports correlation. During the process of MIMO antenna design, it is necessary to minimize the level of correlation in each pair of elements in the structure. Therefore, the received signals from a diversity system should be as independent as possible, and this can be assessed using the correlation coefficient (this coefficient should be the lowest as possible), that can be defined by (see [43]):

\[
p_e = \frac{|S_{11}S_{12} + S_{21}S_{22}|^2}{((1 - (|S_{11}^2| + |S_{21}^2|))(1 - (|S_{22}|^2 + |S_{12}|^2)))}
\]  

(4.3)

4.3.2 Antenna efficiency

Antenna efficiency is a relevant parameter when evaluating a small dimension MIMO antenna’s performance, and it is defined as the relationship between the antenna’s radiated power and its total available power [44, 45].

\[
\eta = \frac{P_{rad}}{P_{available}}
\]

(4.4)

This parameter can be computed by almost all commercial antenna simulation software, by terminating all non-excited ports with 50 Ohm impedance loads. It is also possible to compute using different methods such as Radiometric Method, Resistance Comparison, Random Field Method, among other examples [46]. It is not possible to characterize diversity and MIMO antennas without knowing element patterns explicitly. In this thesis there is no intention to explore antenna efficiency as a main issue. Therefore, the presented results have been obtained by a numerical simulation, using CST Microwave Studio®.

4.3.3 Diversity gain

Diversity gain is a figure of merit used to quantify the performance of diversity technique. It is a slope of the error probability curve in terms of the received SNR in a log-log scale. A good diversity gain value results in a good SNR relation. To measure this coefficient it is necessary to consider the total radiation efficiency and the correlation coefficient (4.5).

\[
DG = \eta_{radiation} \sqrt{1 - |\rho|}
\]  

(4.5)
The diversity gain equation clearly shows that the lower the correlation coefficient, the higher the diversity gain. Therefore, a good isolation between antenna's elements is required, otherwise DG will not reach the desired values [47].

Later, when displaying the simulated structures, an analysis of the Correlation coefficient and diversity gain will be made in order to choose the final manufactured structure.

4.4 Design and simulation of two-element MIMO antennas

This section will explore several structures composed by two elements of reference described in past section 4.2. The structure that shows the best performance is manufactured and the measured results are presented on the next chapter.

The following sections present different configurations and an analysis is made in terms of radiation pattern, S-parameter, Correlation Coefficient and Diversity Gain. Different types of diversity are addressed (polarization diversity and spacial diversity) and the distance between elements will be tested.

All presented configurations are a basic addition of two referenced elements spaced by a substrate layer of 10mm (approximately $\lambda/12$ of the lowest frequency band).

It is important to note that, in every 2-element antenna that will be proposed in this section, "port 1" refers to the element displayed on the left and "port 2" the other one.

Figure 4.10(a) refers to a structure that is composed by two reference elements displayed parallel to each other (spacial diversity).

Observing the S-parameter present in figures 4.10(b) and 4.10(c), it is easy to see that curves $S_{11}$ and $S_{22}$, and $S_{12}$ and $S_{21}$ are impossible to distinguish. It is an expected result, as the structures represented are symmetrical ($S_{11} = S_{22}$ and $S_{12} = S_{21}$). It is noted that some mutual coupling between ports 1 and 2 is present, specially of the resonant frequencies (it's concluded because curves $S_{11}$ and $S_{22}$ overlap on $S_{12}$ and $S_{21}$). However, the resonance at the higher frequency has registered a shift for lower frequencies (approximately 5.6GHz), which can be possible due to the mutual coupling registered. The correlation coefficient between ports shows satisfactory results, despite showing a peak very close to 5.3GHz that agrees with the minimum observed in the diversity gain plot.

The following proposed structures will explore polarization diversity in order to increase the antenna's performance, facing the problems reported by the configuration presented in figure 4.10.
Figure 4.10: Geometry, S-parameter, diversity gain and port correlation coefficient of the structure designed with spacial diversity.
Figure 4.11: Geometry, S-parameter, diversity gain and Port correlation coefficients of a structure designed with polarization diversity, the element on the left is displayed horizontally, while the other vertically.
Figure 4.12: Geometry, S-parameter, diversity gain and port correlation coefficients of a structure designed with polarization diversity, the element on the left is oriented according to the Y axis, while the other on X axis.
Figure 4.13: Geometry, S-parameter, diversity gain and port correlation coefficients of a structure designed with polarization diversity, similar to the figure 4.12(a). The elements are spaced with 20mm.
Figure 4.11 illustrates a two-element MIMO antenna using polarization diversity. The element on the left is placed horizontally, while the other is placed vertically, according to the perspective presented in figure 4.11(a) (the elements are placed orthogonally, resulting in polarization diversity). Comparing the results obtained with the structure previously investigated, it is concluded that mutual coupling has decreased, as well as the peaks of the correlation coefficient (approximately 0.08, figure 4.11(d)) and, consequently, the minimum on the diversity gain has increased (approximately 9.6, figure 4.11(e)). However, the resonance at the higher frequency has shifted again to a lower frequency and it still does not fulfill the requirements for a WLAN antenna (2.45 and 5.8GHz).

Figure 4.12 shows a similar structure presented in 4.11, but this time with inverted elements: the element on the left vertically and the other displayed horizontally. Thus, the elements are orthogonally disposed and polarization diversity is applied.

Observing figures 4.12(b) and 4.12(c) it is concluded that the results are good: both resonances are at the desired frequencies (the value at 2.45 and 5.8GHz for $S_{11}$ and $S_{22}$ are -27 and -22dB and -16 and -14dB, respectively). It is also noticed that the signals are completely uncoupled, which results in a good port correlation coefficient (the worst value is 0.027) and diversity gain (9.87).

Figure 4.13 exhibits the same geometry shown on 4.12(a) in a larger scale in order to increase the space between the elements and therefore increase the isolation between them.

The results regarding the S-parameter are good as is shown in figures 4.13(b) and 4.13(c). Correlation coefficient and diversity gain graphs also show reasonable values.

Looking at the S-parameter results, signals appear to be perfectly decoupled. However, overall results are not better than those presented in figure 4.12. Furthermore, this geometry represents a higher overall size, which is an important factor in order to choose the best structure for WLAN applications (specially for mobile applications).

Analysing the discussed structures, the one that turns out to be the best solution for WLAN applications is the antenna simulated and presented in figure 4.12. Thus, the radiation patterns for each port in each of the resonant frequencies will then be presented.
4.4.1 Radiation pattern

Ideally, a MIMO antenna for Local Area Networks intends to achieve a 360 degree radiation plan in order to reach every direction (omnidirectional radiation pattern), and thus, to reach all the connected devices.

![Radiation pattern images](image)

Figure 4.14: Radiation patterns refering to the structure presented in figure 4.12 at 2.45 and 5.8GHz (3D)

Figure 4.14 shows the behaviour of the antenna illustrated in figure 4.12 when ports 1 and 2 are excited at the resonant frequencies (2.45 and 5.8GHz). Polar representation is presented in figure 4.15 and it is concluded that not all directions are reached using this geometry. It is observed that for the lower resonant frequency the main lobe’s angular width is positive, unlike at 5.8GHz (which is expected, looking at the lower resonance at this frequency). It is seen that this structure does not radiate in all sectors (there is no main lobe achieving the negative degrees for the 90 degrees azimuth). However, a reasonable portion of the space is achieved.
Figure 4.15: Radiation patterns referring to the structure presented in figure 4.12 at 2.45 and 5.8GHz, polar representation.
4.5 Design and Simulation of a four-element MIMO Antenna

As was referred in chapter 2, particularly in figure 2.3, by increasing the number of antennas presented on a MIMO system, the average capacity of the system increases almost linearly. Thus, adding this proposal to the failure to reach the 360 degree coverage with the antenna presented in the previous section figure 4.12(a), a structure was also studied and simulated with four elements, with a layout as shown in the following figure.

Figure 4.16: Configuration of the 4-element simulated and studied MIMO antenna.

As noted, the structure has four orthogonally arranged elements which ensure diversity polarization. Bearing in mind the above structures, this system has an area of 80x80 mm$^2$. Each element is spaced 10 mm towards its adjacent.

Then the performance level of the S-parameter will be presented, as well as the correlation coefficient and diversity gain between each port.

From here onwards, any references to the "port 1" corresponds to the port/element that is in the lower left corner. The remaining ports are designated according to anti-clockwise direction, i.e., "port 2" is the port of the lower right hand corner, "port 3" is in the upper right hand corner, and finally, "port 4" is associated with the upper left hand corner.

Note the symmetry of the proposed structure. Thus, the S-parameters for each of the ports ($S_{ii}$) all have the same behavior over frequency. Likewise, parameters $S_{ij}$ and $S_{ji}$ also have the same behavior, as well as the parameters between adjacent ports (for example, $S_{12}=S_{21}=S_{14}=S_{41}$). Hence, it is concluded that, with respect to the S-parameter, there are only three curves to be taken into account, specific to each port, represented by a curve between adjacent ports and between remote ports, which are arranged obliquely. This statement is supported by the following figure 4.17.
For these reasons, and for a more neat analysis of the plot in the image 4.18 only the curves that are associated with port 1 are presented. As can be seen, there is a slight coupling at the frequency of 2.45GHz. However, in both the lowest and the highest resonant frequency, it is possible to verify that the desired -10dB are achieved.

Due to the symmetrical structure of the presented antenna, only the results for port 1 were displayed (reflection coefficient and diversity gain).

Figure 4.19 shows the correlation coefficient between adjacent (subfigure 4.19(a)) and oblique (subfigure 4.19(b)) ports. It is observed that there is less isolation between oblique ports. However, in both cases, the great majority of the results are very reasonable, particularly in the two resonant frequencies, as marked in both images.
Figure 4.19: Correlation coefficient for the proposed antenna

(a) Correlation coefficient between adjacent ports

(b) Correlation coefficient between oblique ports

Figure 4.20: Diversity gain for the proposed antenna

(a) Diversity gain between adjacent ports

(b) Diversity gain between oblique ports
Similarly, diversity gain referring to adjacent and oblique ports is shown. Note that the resonant frequency values are very satisfactory (not ignoring the minimum recorded for lower frequencies).

Figure 4.21: Radiation patterns for 4-element antenna, 3D representation at 2.45 and 5.8GHz
Figures 4.21 and 4.22 present the radiation patterns in 3D and polar form respectively. In the figures it is possible to observe that the initial goal considered while projecting a 4-element MIMO structure MIMO radiating in every direction reaching all the sectors (covering of 360°) was obtained. The angular width at -3dB for the frequency of 2.45GHz is of about 65° whereas for 5.8GHz it is considerably less, having only about 30°.
Chapter 5

MIMO antenna system prototypes measurements

5.1 Introduction

This chapter aims to make an explanatory analysis of the entire process involving the prototype created from the manufacturing phase to the final measurements that evaluate the performance of the prototypes.

An explanation of the manufacturing process of the prototype held in the DEEC prototyping is on appendix A.

Then the results of the performance of the prototypes at the level of the S-parameter are presented (the two and four-element MIMO antennas).

For the measurement of the parameters, the vector analyzer E8361A (VNA) from Agilent Technologies was used. Automatic calibration of the measuring cable is meant to be made before the measurement of the S-parameters.

Calibration was performed to obtain the reflection coefficients and mutual coupling of the two elements of the structure of the output SMA connectors. It is necessary to eliminate the effect of the cables on measurements, either in phase delays or losses, as if connecting the ports of the antennas directly to the VNA.

After the results are obtained, they are automatically recorded in a single file with the measured parameters. The measurements in free space were made covering the proximal surfaces with an absorbent material panel of electromagnetic waves to avoid signal reflections to nearby antennas.

A 1-9GHz band was defined with 1601 points, which results on a 5MHz step across the measure band. Coaxial cables of 1.2m were used.
5.2 Two-element MIMO antenna

As mentioned in the previous chapter, the proposed antenna that showed the best performance has been chosen to be manufactured is illustrated in figure 4.12. The mask used for the construction of this prototype is available for consultation on appendix B. However, a failure of communication with the department responsible for the model manufacturing, led to an error that resulted in the antenna print shown in figure 4.11 instead of the initially desired one, as presented in figure 5.1. The mask was printed on the opposite side, resulting in printing of said antenna (the result of a “mirror” type translation). Hence, an analysis is then made of the printed antenna radiation diagram level performance, as it was not done in the previous chapter.

![2-element antenna manufactured](image)

Figure 5.1: 2-element antenna manufactured

![Radiation diagrams](image)

Figure 5.2: Radiation diagrams referring to the structure presented in figure 4.11 at 2.45 and 5.8GHz (3D)
As it can be seen, the behavior of the structure is very similar to that shown in Figure 4.12 (see figure 4.15). However, since the orientation of the elements may be different (directional level), in this case, the sector that is not covered is between $90^\circ$ and $180^\circ$, which raises again the presented problems that have been solved by the design of the 4-element MIMO antenna.

As discussed in the last chapter, the antenna that was built (figure 4.11) did not have of the higher resonant frequency in the band of frequencies intended for WLAN applications (5.8GHz). Thus, it is expected that the -10dB goal will not be obtained in this frequency band, unfortunately.

### 5.2.1 Antenna performance

Four parameters can be measured simultaneously with the used vector analyser, $S_{11}$ and $S_{22}$ parameters were measured first (see Fig. 5.4) and then transmission coefficients were automatically generated $S_{21}$ and $S_{12}$.

The measured values for both resonant frequencies were well below expectations as it is observable in Figure 5.5. The resonance at these frequencies is considerably smaller, which can be explained either by calibration errors, and also in the manufacturing process: the introduction of the SMA connector and the welding of the prototype. Another factor that may be relevant is the value of the spacing between the feed line and cpw, since, as was stated in section 4.2 (figure 4.3(b)), the ideal spacing of the reference element was not feasible in the laboratory where the antenna was fabricated.

Alternatively, the increase in the resonant frequency registered in the antenna measurements can also be explained by the possibility of some of the manufactured antenna measurements to be slightly
lower than the previously simulated model in CST, since a reduction in the antenna length causes a shift in frequency as was shown in figure 4.3(c).

However, it is noted that the resonant frequencies are visible, despite being small and diverting from the desired values and the simulation itself.

Another positive point is that the signals are completely uncoupled, which is one of the main goals when creating a project of a MIMO antenna.
Figure 5.5: S-parameter measured at 2.45GHz and 5.8GHz
5.3 Four-element MIMO antenna

Figure 5.6 shows the manufactured structure corresponding to the simulated model (fig 4.16).

![Figure 5.6: 4-element antenna manufactured](image)

As mentioned above, the vector analyser used to perform the prototype measurement can measure four signals simultaneously. An assembly was made in order to connect the four connectors (as shown in Figure 5.7) to obtain the reflection coefficients and subsequently generate the transmission coefficients.

![Figure 5.7: Setup for the measurement of reflection coefficients of 4-element antenna](image)

The designation adopted for the identification of ports was said in the previous chapter, i.e. the port in the lower left hand corner corresponds to port 1, following the anti-clockwise direction until the last port (port 4).

5.3.1 Antenna Performance

Contrary to what was done in the presentation of the simulation results in section 4.5, S-parameter shown refers to different ports. Each figure illustrates the reflection coefficient of each port as well as the transmission coefficients associated with each one. The results were presented in this way since the
symmetries in the simulated structure are not completely mirrored by the experimental results. Thus, the curves are not superimposed and it was thought to be relevant to present all the obtained signals.

It must also be noted that the results presented below were obtained from the S-parameter Explorer 1.0 software, since the data generated by the VNA were exported in S4P format and it was the most efficient way for data processing and presentation.

Figure 5.8: S-parameters measured (ports 1 and 2)
Figures 5.8 and 5.9 show the results obtained experimentally. As was the case for the two antenna elements, it is observable that the recorded resonance for the desired frequency does not reach the threshold of -10dB, as was intended. However, especially for lower frequency (2.45GHz) the measured value is close to -8dB (5.8dB for the value is about -5dB). Yet, contrary to what was found earlier, the resonances are centered on the desired frequency. Again, in all the situations illustrated above, the signals are completely uncoupled, so one of the main objectives of the MIMO antenna was achieved.

According to the experimental results obtained, the prototype can be used as a wireless router appropriated for indoor environments, according to the IEEE 802.11n standard.
Chapter 6

Conclusions

This chapter aims at presenting the most relevant conclusions of the work done as well as possible suggestions for future development. This dissertation presents a design and study of MIMO antennas for applications to wireless systems that operate in the ISM band of 2.45 and 5.8 GHz.

Firstly, the problem was contextualized, making up a survey of the most widely used wireless technologies. Also, in the same chapter, an explanatory analysis of the fundamental concepts that characterize the MIMO systems and justify its use was presented. In the following chapter, an overview about printed antennas and MIMO antennas was made, where later a state of the art research was presented. In this research various solutions were analysed, and they contributed to the design of the implemented solutions have been analysed.

Chapter 3 presents the structure of the reference element which formed the basis for the realization of MIMO solutions presented later. The reference element was built on a Rogers RT substrate / duroid 5880 having a thickness of 1.575 mm and a dielectric permittivity of 2.2. The element contains only one side of metallised copper and the CPW feed was chosen because it has low coupling and allowed a reduced circuit size, which is a challenge in the construction of a MIMO antenna. The element comprises a circular patch, and was cut in one slot which ensures the resonant frequency of 5.8 GHz (resonance in the lower frequency is provided by the spacing between the feed line and CPW).

The dimensions of all structures were simulated using the CST Microwave Studio software. All the simulations presented in this work were made using this software. The reference element has been re-sized for the need to adjust the spacing between the feed line and CPW to meet the manufacturability of the prototyping department. The element has values in terms of the S-parameter values of less than -20dB in the two resonant frequencies.

Chapter 4 presents several structures with different configurations composed of two elements. The first dummy structure has only spatial diversity. In order to improve the antenna performance, the simulation structures were arranged orthogonally with elements (polarization diversity). There were significant improvements in the results for the S-parameter, both in terms of resonance and the uncoupling of the elements. Then the structure was chosen based on its performance and the overall size of the circuit. The need to design a 4-element antenna was to increase the radiation spatially, in order to obtain the
total coverage of the antenna’s radiation pattern. This was observed only for the simulations.

The structure of the 4 elements is configured based on the structure of 2 elements chosen for manufacture. There was a slight coupling between the reflection and transmission coefficients in the lowest resonant frequency but with quite positive results for both the correlation coefficient and the diversity gain.

All the simulated multi-element structures fulfill the desired goal of -10dB for the reflection coefficients to 2.45GHz and 5.8GHz. The radiation efficiency was studied in both the structures.

Finally, chapter 5 presents all the work done in the process of manufacture and testing phase to obtain the experimental results. The construction and development of the experimental measurements were performed in laboratories Instituto Superior Técnico and the Institute of Lisbon Telecommunications.

A communication failure resulted in printing an antenna mirroring the face of the mask and hence the construction of a structure symmetrical to the desired one (two elements).

Only the S-parameter was measured. An analysis of the structures radiation patterns was carried out since it was necessary to take measurements in anechoic chamber, so there was no opportunity to make these measurements. In both structures the ports were fed simultaneously.

To compare the experimental results with simulated measurements, these were made in free space. For the two element structure, an offset has been registered for frequencies above the higher resonant frequency, which can possibly be explained by the antenna measurements being lower compared to the simulated model (possibly the length of the slot, which influences directly the resonant frequency of 5.8GHz). On the other hand, in the 4-element structure, the resonances were obtained in the expected frequencies.

The results were not according to the expected, in terms of the value of the desired resonant frequency never reaching the -10dB barrier that was initially desired. The discrepancy of the results obtained in the values of the resonance may have occurred for several reasons, including the limitations of the simulation model, imperfections in the solder joints that connect the SMA connector to the antenna feed line, imperfections in the antenna manufacturing and the currents induced in the power cord due to problems caused by CPW, resulting in the small antennas, causing additional resonance in the measurement of parameters.

However, it is noted that in both structures, a decoupling completion of the reflection coefficients and transmission was observed. One possible application for the built antenna is a wireless router indicated for indoor environments.
6.1 Future Work

Although some of the proposed objectives have been achieved in the view of the author, there are still some aspects to be improved, as well as some objectives to achieve including:

- Printing and measuring the structure of two elements originally intended;
- Improvement of the reference element, and consequently the MIMO built structures to increase the resonance in the desired frequency;
- Taking measurements in order to obtain the efficiency of structures and their radiation patterns;
- Possible application of a filter between the elements of the fabricated structures to enhance the antenna resonance and the elements isolation;
- Measurements of diversity gain through a reverberation chamber in order to obtain an accurate measurements of the diversity gain;
- Improving manufacturing techniques of printed circuitry to reduce the limitations imposed by the current process;
- Measurements of the manufactured structures in a router environment (for instance, in the presence of other electronic circuits inside of a plastic box).
References


[21] E. Mohamed and A. Abdulsattar, “Evaluation of mimo system capacity over rayleigh fading channel.”


Appendix A

Manufacturing process of printed circuits

This section aims to make an analysis and explanation of the process of the construction of the two antennas manufactured. This whole process was done in DEEC prototyping room located in the north tower of the Instituto Superior Técnico. After creating models of the antennas in CST Microwave Studio®, they were printed on photographic film to minimize precision errors due to the reduced thickness between the feeding line and CPW (0.12 mm) and the distance between the U-slot and the edge of the circular patch.

The mask was created from the model in AutoCAD (available in appendix B) and subsequently sent to the person responsible for printing.

The procedure used is highly practical and inexpensive when preparing single circuits or a small series of circuits [48].

In order to be printed, the surface of the chosen substrate must be cleaned with a good detergent, to become free from impurities. Then, it must be dried in a specific oven, taking extreme care to avoid any fingerprints on the board surface.

Then there was the production of the printed circuit, using as a basis the photographic film. In the production of printed circuit photolithographic process was used. This process is the transfer of the geometry of a mask to a surface, in this case using copper, after being illuminated by ultraviolet radiation. The copper surface which is not illuminated is removed using various chemicals.

The chemicals used for the etching process are called photoresists, which are organic polymers that change its chemical characteristics when exposed to ultraviolet light.

Subsequently 6 SMA connectors were soldered (50 Ohm impedance) so as to feed the aggregate elements, as is shown in figure A.1.
Figure A.1: Prototype after soldering the connectors
Appendix B

Autocad Mask
Appendix C

SMA connector

Figure C.1: SMA connector

(a) Farrel SMA connector

(b) Connector Model