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Mechanically flexible antenna design for a multimedia "2 wheeler" segment

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Resumo

A necessidade da população estar permanentemente conectada entre si de uma forma segura, rápida e eficiente proporciona uma constante evolução da tecnologia e em particular da tecnologia das comunicações. Tendo em conta esta evolução, foi também importante acrescentar valor ao nível da conectividade em grande parte dos dispositivos electrónicos.

Assim, surgiu a necessidade de introduzir este tipo de tecnologia nos painéis de controlo dos veículos de duas rodas, com o objectivo de proporcionar ao utilizador uma experiência completa e segura. Para tal, pretende-se obter como resultado final uma melhoria da solução actual, que devido à baixa eficiência das antenas utilizadas apresenta algumas fragilidades a nível de conectividade. Este trabalho tem como objectivo final o desenvolvimento de uma antena capaz de proporcionar a utilização do telemóvel através do painel de controlo e conectado aos capacetes, permitindo, por exemplo, a realização de chamadas telefónicas ou a escolha de músicas.

Na situação actual, são utilizadas chip antennas, escolhidas devido à sua fácil implementação e pequena dimensão, contudo apresentam uma eficiência muito reduzida, não podendo ser consideradas a solução ideal. Desta forma, ao longo desta dissertação será estudada e analisada uma diferente implementação, recorrendo a soluções diferentes e tendo sempre em conta o espaço disponível, o custo de produção e a implementação na linha de produção. Esta antena deve funcionar para as bandas Wi-Fi e Bluetooth, para tal a frequência central será 2.45 GHz e a largura de banda terá de ser compreendida entre 2.4 GHz e 2.5 GHz. Ao longo deste trabalho será utilizado o Computer Simulation Technology (CST) para o desenho e simulação da antena a incorporar e posteriormente a prototipagem e caracterização na câmara anecóica a fim de confirmar os resultados obtidos em simulação.

Abstract

The need for the population to be permanently connected to each other has arisen. In light of that, the world requires the constant evolution of technology and in particular of communications technology. In view of these developments, it has also been important to add connectivity value in most electronic devices.

In light of this, the need of introducing this type of technology in the control panels of two-wheeler vehicles had increased, however, this must provide the user a complete and safe experience. For this, it is intended to obtain as an end result an improvement of the current solution, which currently has a poor performance. This Master Thesis aims an antenna implementation capable of allowing the use of a mobile phone through the control panel. This device will be connected to its user helmet, which allows, for example, to make phone calls or even choose his favourite music.

In the current situation, chip antennas are used, chosen due to their easy implementation and small size. However they have a very low efficiency and therefore are not the ideal solution.

Hence, all over this dissertation, a different implementation will be studied and analysed, using different solutions and always taking into account the space available, the cost of production and its implementation in the production line. The built antenna should work for the Wi-Fi and Bluetooth bands, so the center frequency will be 2.45GHz and the bandwidth will have to be between 2.4GHz and 2.5GHz. Throughout this work will be used CST for the design and simulation of the antenna and later prototyping and characterisation in the anechoic chamber in order to confirm the results obtained in simulation.

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Be less curious about people and more curious about ideas.

Marie Curie

Contents

1	Introduction	1
1.1	Context	1
1.2	Motivation	2
1.3	Objectives	2
1.4	Document Structure	3
1.5	Contributions	3
2	Literature Review	5
2.1	Antenna Theory	5
2.1.1	Fundamental Parameters	5
2.1.2	Radiation Pattern	5
2.1.3	Radiation Power Density	7
2.1.4	Radiation Intensity	8
2.1.5	Beamwidth	8
2.1.6	Directivity	8
2.1.7	Antenna Efficiency	9
2.1.8	Gain	9
2.1.9	Polarisation	10
2.1.10	Antenna Impedance	10
2.2	Types of antennas	11
2.2.1	Chip antennas	12
2.2.2	Dipole antennas	12
2.2.3	Microstrip antennas	13
2.3	Types of implementations	14
2.3.1	Metallic structure	14
2.3.2	Flexible implementation	14
2.3.3	Conductive ink process antenna	15
2.3.4	Laser Direct Structuring	16
2.4	Summary	17
3	Antenna considerations	19
3.1	Dipole Antennas	19
3.2	Inverted-F antenna (Inverted-F antenna (IFA))	20
3.2.1	IFA dimensions	21
3.2.2	Feed dimension	22
3.2.3	Impedance Matching Network	24
3.3	Summary	26

4	Antenna Design	27
4.1	Proposed Solution	27
4.1.1	Metallic structure	28
4.1.2	Flexible implementation	28
4.1.3	Printed antennas	28
4.1.4	Laser Direct Structuring	29
4.1.5	Selected Technology	29
4.1.6	Selected Antenna	29
4.2	IFA project	29
4.2.1	Connector Response	29
4.2.2	Antenna Material	31
4.3	Antenna Design	31
4.3.1	Antenna Design with connector	34
4.3.2	Impedance Matching Network	36
4.3.3	Folded Antenna	37
4.4	Integration of the flexible antenna on cluster	40
4.5	Prototyping	42
4.5.1	Final model	43
4.5.2	Base Printed Circuit Board (PCB) and Antenna Flexible PCB Layouts . .	45
4.6	Summary	46
5	Antenna characterisation and results	47
5.1	Connector	47
5.2	Flat Antenna	48
5.3	Folded Antenna	50
5.4	Summary	51
6	Conclusions and Future Work	53
6.1	Conclusions and Remark	53
6.2	Future Work	54

List of Figures

1.1	Control panel.	2
2.1	Example antenna radiation pattern in a Cartesian coordinate system [1].	6
2.2	Example antenna radiation pattern in a polar coordinate system [2].	6
2.3	Three-dimensional antenna pattern [3].	7
2.4	Illustration of a radiation pattern with beamwidth analysis [4].	8
2.5	Different types of polarisation [4].	10
2.6	Example of an chip antenna [9]	12
2.7	Illustration of meandered monopole.	13
2.8	Illustration of a microstrip patch antenna [11].	13
2.9	Metallic antenna that could be assembled on PCB [13].	14
2.10	Example of a flexible circuit[14].	15
2.11	Example of a printed circuit using a desktop printer[17].	16
2.12	Example of an Laser Direct Structuring (LDS) automotive implementation [18]. .	16
3.1	Illustration of a half-wave dipole antenna, with reference of current and voltage behaviour.[21]	19
3.3	Illustration of a IFA.	21
3.4	Example of a section of coplanar waveguide with ground [24].	22
3.8	Location of the load on Smith-chart and respective impedance matching network[25].	25
4.1	Side view instrumentation cluster.	27
4.2	Connector, flexible and PCB models in CST	30
4.3	Connector simulation response.	30
4.4	Connector simulation with some measurements.	31
4.5	Flat antenna and most important dimensions.	32
4.6	Results of reflection coefficient of the simulated antenna on CST.	32
4.7	Flat antenna with complete feed and most important dimensions.	33
4.8	Flat antenna comparison with feed different dimensions, through a Smith-Chart. .	33
4.9	Flat antenna comparison with feed different dimensions, through a S -Parameter Chart.	34
4.10	Model of the flat antenna on flexible substrate,Flexible Printed Circuit/Flexible Flat Cable (FPC/FFC) and PCB for simulation on CST.	34
4.11	Results of reflection coefficient of the simulated antenna, connector and PCB on CST.	35
4.13	Simulation Three-dimensional (3D) radiation pattern of of the simulated flat an- tenna, connector and PCB on CST.	36

4.14	Smith chart where the point 1 is the initial point, moves along the arrow until the point 2 where the capacitor was inserted, finally the point 3 located in the final impedance after the insertion of the inductor.	36
4.18	Simulated folded antenna with a matching network.	39
4.20	Simulated 3D radiation pattern of the folded antenna.	40
4.22	Simulated return loss of the flexible antenna model with the display backcover.	41
4.24	Simulated radiation pattern 3D of the flexible antenna with the display.	42
4.25	Simulated return loss of flexible antenna with display, with substrate thicknesses of 0.085 mm and 0.125 mm and copper thickness of 0.035 mm and 0.012 mm respectively.	43
4.26	Simulated return loss comparison between the both antennas with display.	44
4.28	Simulated 3D radiation pattern comparison between the both antennas with display.	45
4.29	Layout implementation.	46
5.1	Prototypes of the flexible antenna, connector PCB and FPC/FFC connector.	47
5.2	Measured S-Parameters of the connector PCB to the antenna PCB, through FPC/FFC connector.	48
5.3	Simulated versus measurements of the return loss from the flat antenna through the connector and the PCB.	49
5.4	Measured return loss of flat antenna with a matching network.	49
5.6	Simulated (red) versus measured (green) return loss of folded antenna inside of the instrument cluster.	50

List of Tables

4.1	Comparison of all different possibilities of implementation.	29
4.2	Comparison between the radiation proprieties to the both models.	43
4.3	Simulated antenna parameters comparison between the both antennas with display.	44
4.4	Final IFA dimensions with refer of 3.3	45

Acronyms and Abbreviations

2D Two-dimensional

3D Three-dimensional

CST Computer Simulation Technology

FIT Finite Integral Technique

FNBW First null beam width

FPC/FFC Flexible Printed Circuit/Flexible Flat Cable

HPBW Half-power beam width

IFA Inverted-F antenna

ILA Inverted-L antenna

LDS Laser Direct Structuring

PCB Printed Circuit Board

RF Radio Frequency

VNA Vector Network Analyzer

VSWR Voltage standing wave ratio

Chapter 1

Introduction

Since the wireless communications are, nowadays, an important differentiator in all devices, especially since the dawn of the IoT era, connectivity has become an integral part of all electronic devices. Hence, Bosch CM (Car Multimedia) wants to improve the connectivity it can provide on the instrumentation cluster devices for motorcycle vehicles. Because the main focus of this work represents the Wi-Fi and Bluetooth communications between the control panel and the user components, it is important to improve the actual implementation, that utilises a standard antenna incorporated on the PCB of the control panel. This happens because Bosch Car Multimedia aims to improve its current implementation. Hence, this work will allow the enhancement of the company 2Wheelers communication related services, focusing on upgrading its current premium sector.

1.1 Context

In the last years, the connectivity between persons has changed, because of that, the way as we see the interaction between people and their motorcycle had the necessity of change too. Due to the need to escape from traffic or for the simple pleasure of riding a 2Wheeler, being an important part of automotive business, the number of motorcycle users has increased

The premium segments on the automobile industry have always pushed for the boundaries of technology, motorcycles are no exception, and in this segment, the premium brands and models are demanding more and more advanced digital solutions for their vehicles. The instrumentation cluster of motorcycles are now required to have connectivity, both Wi-Fi and Bluetooth, and for that, they require RF electronics. While most of these electronics come bundled in integrated packages with a lot of digitalisation on it, the antennas are still a bottleneck in many cases. Due to space, price, or manufacturability constraints, the antennas are many times sub-par to their systems, undermining the potential performance. Therefore, it has become apparent that there is a need for research and development of custom solutions that can juggle all the constraints and deliver a solution capable of boosting performance beyond the state of the art on these devices.



Figure 1.1: Control panel.

1.2 Motivation

As consequence of the increasing number of WI-Fi and Bluetooth devices the communication technology on the motorcycles should consequently improve. This would allow the motorcycles control panel to provide an improved user interactivity and a better performance in communications fields. It should be noticed that the current implementation enables for a good communication process to occur. However, premium sectors demand for a better solution at all constraints levels that would allow its users to take the most of their driving experience. At this time, almost all the 2Wheelers solutions have a chip antenna incorporated on their PCB. By doing this way, the solution doesn't offer the perfect package at a communication level. Because this chip antennas are not the best solution for this application, other types of implementations were studied with the purpose of trying to achieve better results.

1.3 Objectives

This dissertation main goal is to improve the performance of the antenna that is integrated in the motorcycle control panel. In a practical implementation, this is noticeable if a good connection between the cluster, the helmets and the smartphone happens to be established. In order to better characterise this Master Thesis objectives, some points need to be procured. They are:

Radiation pattern - Firstly, the radiation pattern must be well defined with the most omnidirectional pattern it can achieve.

Central frequency - Bluetooth and Wi-Fi comprising - The bandwidth of this antenna needs to reside on a 2.45GHz central frequency and be comprised between 2.4GHz and 2.5GHz. This allows the user to connect via the Bluetooth and Wi-Fi wireless technologies.

Efficiency -In order to represent a better solution when compared to the existent one, the efficiency should be at least 50%.

Space - Since the space within the cluster is very limited, this work solution should also try to create the smaller antenna it can.

Production line - Another important item is the introduction of an extra process to the production line and the cost that this can add to the product.

Cost - As this is a commercial product, the final price of our product is a point to take care.

1.4 Document Structure

This document is comprised of five chapters. In Chapter 1 the context, motivation, objectives, document structure and contribution are explained. The Chapter 2 have as content the literature review in antenna theory and design. In Chapter 3 the IFA antenna is explained and some considerations were taken. In Chapter 4 the antenna design and all the process to achieve that is shown. In Chapter 5, the prototype of the antenna and its results are compared with the simulation. Finally, the Chapter 6 is the conclusion of this master thesis.

1.5 Contributions

This work is in the telecommunications area and it involved the design and characterisation of an antenna that is intended to be implemented on the automotive sector. As part of this work some contributions were made, namely:

- Investigation of new approaches for the design of flexible antennas;
- Study and design of a flexible IFA antenna;
- Simulation and improvement of the designed model;
- Layout of the achieved results;
- Prototype development;
- Test and comparison with the simulation results.

Chapter 2

Literature Review

In this chapter a literature review will be performed. To begin, section 2.1 describes the antenna theory. Furthermore, in section 2.2, different typologies of antennas and their characteristics will be shown. Lastly, in section 2.3 possible new implementations to introduce in this thesis will be analysed and discussed.

2.1 Antenna Theory

2.1.1 Fundamental Parameters

Since the fundamental parameters of an antenna are known, its characterisation and development become easier. This characterisation consists in several factors, namely, radiation pattern, radiation power density, radiation intensity, beamwidth, directivity, antenna efficiency, gain, beam efficiency, bandwidth, polarisation, input impedance and many others.

2.1.2 Radiation Pattern

The radiation pattern of an antenna is a plot of the radiated field/power as a function of the angle at a fixed distance, which should be large enough to be considered far field [1]. It can be plotted as a radiation pattern plot, in Two-dimensional (2D) (with a Cartesian coordinate system or in a polar coordinate system) or 3D, both representations are important and can give different and several information aspects. In the Cartesian radiation pattern the radiated field distribution is shown as a function of angle and in space.

Through this type of plot, some information can be taken such as [1]:

- the main lobe Half-power beam width (HPBW);
- the First null beam width (FNBW);
- the first side-lobe level;
- the front-to-back ratio;

- null positions;

This information can be observed in the radiation pattern on figure below 2.1.

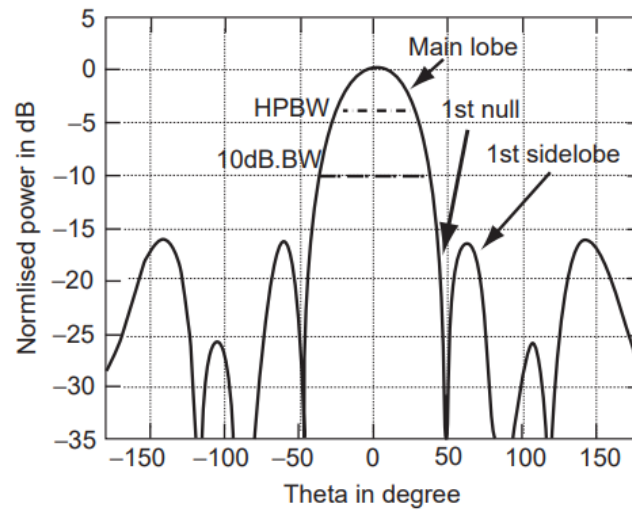


Figure 2.1: Example antenna radiation pattern in a Cartesian coordinate system [1].

On the other hand, if a radiation pattern is produced in a polar coordinate system like in the figure 2.2, the analysis of this information is made in a different mode. Firstly, the antenna is placed at the graph origin and the gain of the antenna is measured at various angles. For this reason, and because it is a 2D plot, three radiation pattern graphs from different directions are provided for one antenna. This type of plots suffers changes with frequency growing, hence, this graph should be plotted regarding the precise frequency of operation.

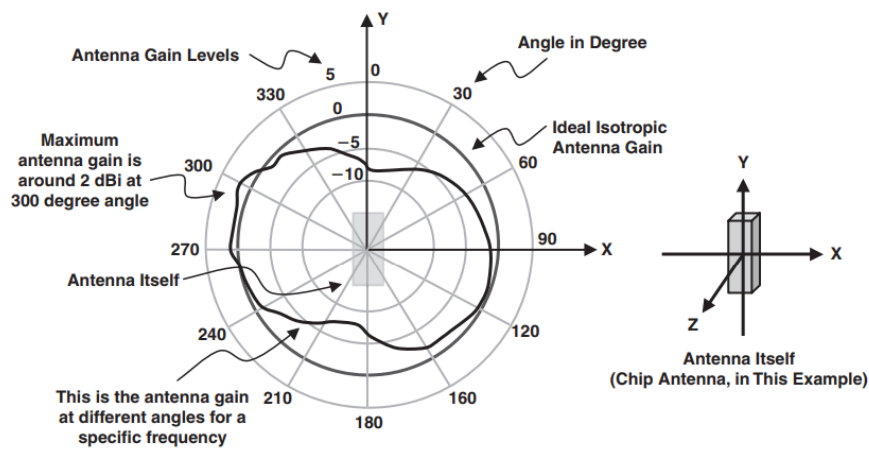


Figure 2.2: Example antenna radiation pattern in a polar coordinate system [2].

Then, the combination of all the plots, results in the 3D plot, as shown in figure 2.3.

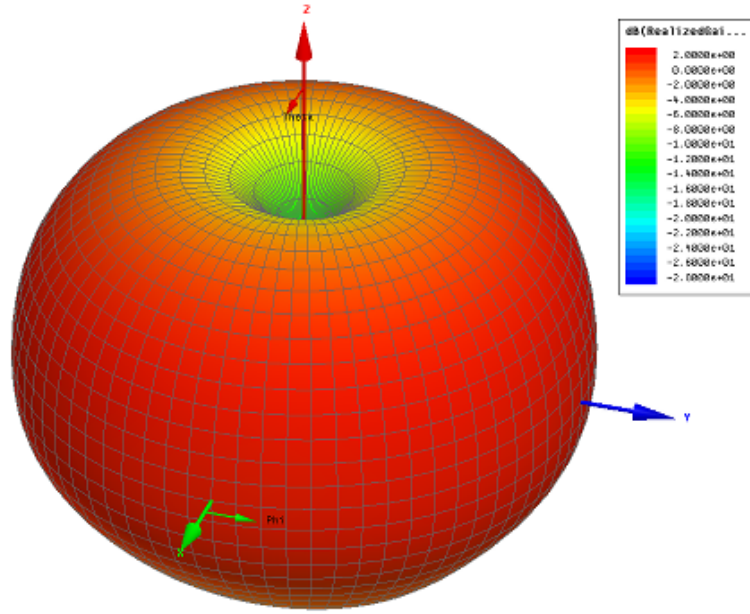


Figure 2.3: Three-dimensional antenna pattern [3].

2.1.3 Radiation Power Density

The electromagnetic waves are utilised to transport data, either on free spaces or on a surface [4]. As a result, both power and energy are associated with the magnetic field. With the help of the instantaneous *Poynting* vector, as described in Equation 2.1.

$$\mathcal{W} = \mathcal{E} \times \mathcal{H} \quad (2.1)$$

where $\mathcal{W}$ is the instantaneous *Poynting* vector, $\mathcal{E}$ the electric field and $\mathcal{H}$ the magnetic field. Through this equation (2.1) it is possible to determine the instantaneous power that crosses that surface.

$$\mathcal{P} = \oint_S \mathcal{W} dS. \quad (2.2)$$

Here $\mathcal{P}$ is the instantaneous total power and S the surface it crosses. From these equations, we arrive at the average power density Equation 2.3

$$W_{av} = \frac{1}{2} \text{RE}\{\mathbf{E} \times \mathbf{H}^*\} \quad (2.3)$$

Finally, the power radiated P_{rad} is shown in Equation 2.4

$$P_{rad} = \oint_S W_{av} dS = \oint_S \frac{1}{2} \text{RE}(\mathbf{E} \times \mathbf{H}^*) dS. \quad (2.4)$$

2.1.4 Radiation Intensity

Radiation intensity in a given direction is defined as the power radiated from an antenna per unit solid angle[4]. This parameter can be obtained by multiplying the density of radiation, W_{rad} , by the square of the distance, r .

$$U = Wr^2 \quad (2.5)$$

2.1.5 Beamwidth

The beamwidth of a pattern is defined as the angular separation between two identical points on opposite side of the pattern maximum [5]. This parameter can be determined using different definitions, by HPBW or by FNBW. The FNBW is the angular separation between the first nulls in the pattern [5]. Another parameter is the HPBW that is characterised by the angular separation where the radiation intensity is maximized. The beamwidth is directly related with lateral lobes. So, as the beamwidth decreases the lateral lobe increases and counterwise, it can also be used as an antenna resolution parameter. The directivity of an antenna will be the greater as the smaller the beam width at -3dB. As can be seen in the figure 2.4.

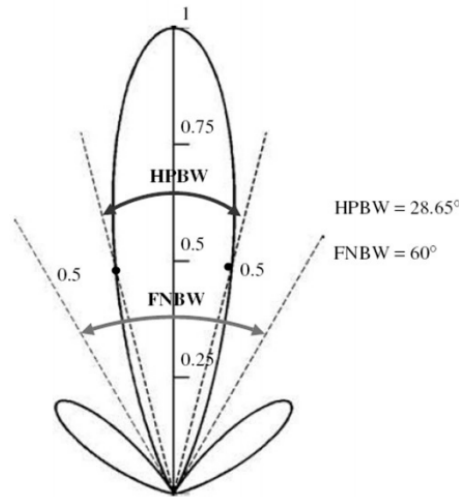


Figure 2.4: Illustration of a radiation pattern with beamwidth analysis [4].

2.1.6 Directivity

The directivity of an antenna is defined by the concentration of the power radiated by the antenna in a particular direction, otherwise the direction is considered to be the direction of the maximum

radiation intensity. As a result the Equation 2.6 :

$$D = \frac{4\pi U}{P_{rad}} \quad (2.6)$$

2.1.7 Antenna Efficiency

The antenna efficiency is directly related to the conversion that the antenna makes through the received electrical signals into electromagnetic waves. The total efficiency of an antenna can be calculated by multiplying the losses that occurs on conversion, where e_r represents the reflected efficiency and e_{cd} the antenna radiation efficiency [6].

$$e_0 = e_r e_{cd} \quad (2.7)$$

The losses due to misadaptation are considered in the reflection efficiency, where it is necessary to take into account the reflection coefficient at the antenna terminals. Considering the input impedance and the impedance of the characteristic line,

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (2.8)$$

and the reflected efficiency,

$$e_r = 1 - |\Gamma|^2. \quad (2.9)$$

The radiation efficiency of an antenna arises since losses of several orders occur, causing the P_{in} input power to be less than the radiated P_{rad} power.

$$e_{cd} = \frac{P_{rad}}{P_{in}} \quad (2.10)$$

Culminating in a total efficiency

$$e_0 = \frac{P_{rad}}{P_{in}} (1 - |\Gamma|^2). \quad (2.11)$$

2.1.8 Gain

The gain is directly related to the directivity of an antenna, it represents the ratio of the intensity of radiation in a given direction to the power that would be delivered to the antenna if it were radiated in an isotropic manner

$$G = 4\pi \frac{U}{P_{in}} \quad (2.12)$$

In a relationship between directivity and gain,

$$G = eD. \quad (2.13)$$

2.1.9 Polarisation

The polarisation corresponds to the figure described over time by the end of the electric field vector at a given point in space and the direction in which that figure is drawn, when viewed in the direction of propagation of the electromagnetic wave [6].

Thereby, the polarity of an electromagnetic wave is the direction of the electric field. There are three polarisation types:

- circular - the phase of the electric field has constant speed and rotate along the circle;
- elliptic - phase and amplitude of the electric field have not constant speed and this provokes an elliptical form;
- linear (vertical and horizontal) - in this type of polarisation, the electrical field has no rotation, is straight.

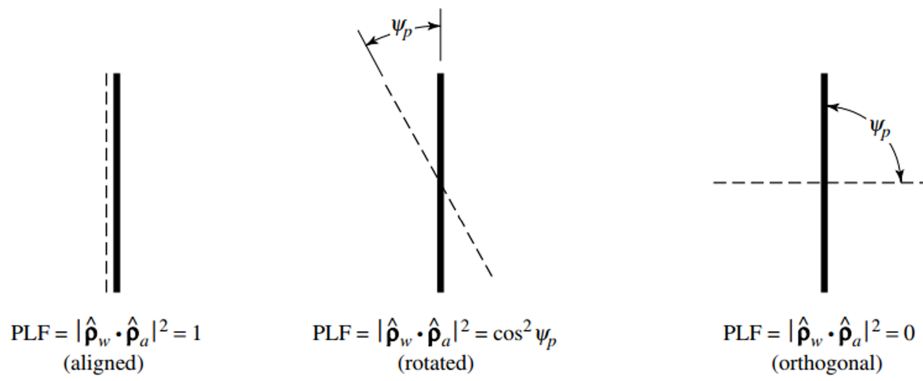


Figure 2.5: Different types of polarisation [4].

This parameter can suffer with a lot of conditions, like the way the antenna launches electromagnetic waves, the environment that can make some changes and cause losses and depending on the the receiver / emitter characteristics. If the receiving and transmitting antennas are different, or have different polarisation, polarisation losses may occur, because the power transferred between the two antennas are not maximised.

2.1.10 Antenna Impedance

An antenna is normally part of an RF circuit and has the ability to convert guided electromagnetic waves into radiated electromagnetic waves and vice-versa [2]. When the impedance of an antenna is mismatched with the rest of the RF circuit impedance reflections or differences relative to power transference can occur, this phenomenon can induce in faults of the antenna efficiency.

The antenna impedance has some characteristic such as: is the same when the antenna is on receive or transmission mode; changes with the frequency; antenna impedance depends on the

shape and size of the antenna; to analyse the impedance or take some conclusions the antenna can be replaced by an equivalent impedance connected to the ground.

On practical experience, this information can be plotted on the Voltage standing wave ratio (VSWR) graph or with the plots of the S-parameters. In order to achieve a certain impedance between the antenna and the rest of the RF circuit one of two processes can be taken. They are antenna matching or the antenna tuning. The antenna matching does the adaptation, adding passive elements as capacitors, inductors or resistors, on the other hand the antenna tuning is made by resizing and/or reshaping an antenna with the objective to reach the impedance that is pretended.

2.1.10.1 Voltage Standing Wave Ratio

One of the most utilised parameters to characterise an antenna is the VSWR, that is the measure of how efficiently radio-frequency power is transferred from a power source into a load [2]. This parameter is a result of a study about impedance and the matching between, in this case, the antenna and the rest of the circuit.

On practical experience, is a ratio of the maximum among the minimum of a undesired signal wave. When VSWR is equal to 1, the signal is pure and is a perfect match. If the value is higher, until 2, the impedance is acceptable and close to the wanted, but if this value is more than 2, the antenna is not perfectly tuned. Now, VSWR is simply defined as a ratio. A ratio of 1:2 signifies that 90% of the source power is transferred to its load which is equivalent -10dB. This leads to the value of 2 to be considered among the community as a standard reference. However, smaller antennas do not require such an higher value. Hence, in the smartphone industry this parameter is considered to be acceptable when its value is 1:3. This means that 67% of the antenna source power goes directly to its load and 33% is still reflected. It must be noticed that in a smartphone this is considered to be acceptable, but not perfect.

2.1.10.2 Scattering parameters

The scattering parameters or S-parameters have as main function measure and characterise the circuit on point of the view of the electrical system. This shows the reflection back to the source and transmission to other directions when the signal is electromagnetic wave. The S-parameters turns the analyses of the attenuation or amplification of a wave easier, since the wave is evaluated when the wave is transmitted through the circuit. [7]. And can be plotted as a Smith Chart or in magnitude.

2.2 Types of antennas

Nowadays, several types of antennas are well known and implemented in different types of devices. For different types of applications different types of antennas can be used, this antennas can

be divided into multiple groups of antennas, such as wire antennas, log-periodic antennas, travelling wave antennas, reflector antennas, aperture antennas, microstrip antennas and many other types. However, in order to implement in a small and restricted space only some typologies are available. However, for this work solely addresses the ones that could fit in a confined space, which are considered to be interesting and represent a study target. So, for that purpose, dipole antennas, microstrip antennas, slot antennas and inverted-F antennas were studied, starting by the chip antenna that is already used in the project.

2.2.1 Chip antennas

A chip antenna is a product built with the purpose of being easily integrated into embedded systems by being directly soldered into a PCB as a normal SMD component. They were also developed to be easily tuned to the correct frequency of operation, since they depend on the overall PCB structure to work as radiative element. It is one of the most utilised antennas due to their small footprint, cost and easier implementation by the user. Additionally, since that is mostly implemented with portable products, a chip antenna is less subject to detuning. However, this typology implies a lot of constraints as lower gain, and several requests to work properly, such as the size between the antenna and the reference ground plane and the size of cleaning space area on PCB [8].

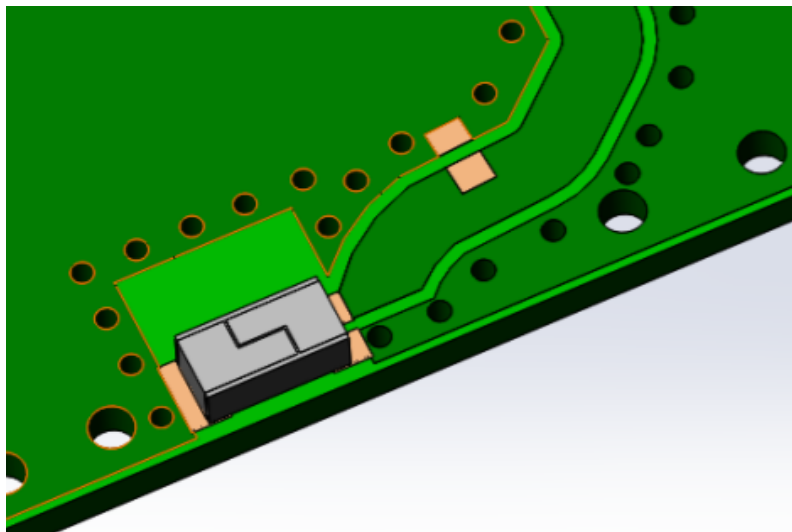


Figure 2.6: Example of an chip antenna [9]

2.2.2 Dipole antennas

This category of antennas is the simplest and oldest of all. Inside of this category several variations of dipole antennas exist, they are short dipole antennas, dipole antennas, half-wave dipole and monopole antennas, that have some changes in different aspects, such as the length in comparison with the wavelength, the gain, the radiation pattern, among others. In a basic explanation this dipole is simply a long wire, which can be inserted above the air or on substrate.

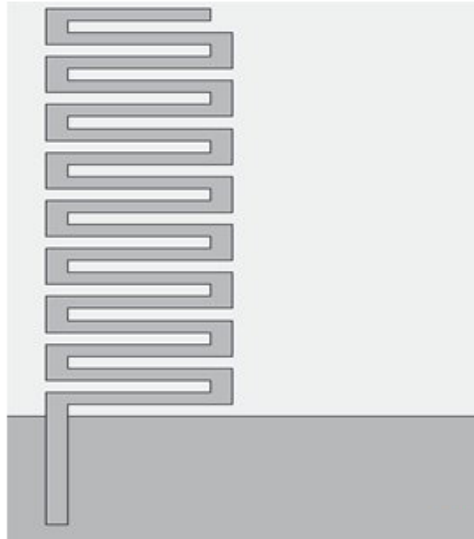


Figure 2.7: Illustration of meandered monopole.

2.2.3 Microstrip antennas

In this category two typical forms of antennas can appear such as rectangular microstrip (patch) antenna. A microstrip antenna consists of a thin metallic conducting patch etched on a grounded dielectric substrate [10]. This typology has emerged as a variation of this microstrip transmission line. Since that planar antenna could be pretended, the biggest advantage of this element can be printed onto a circuit board. In this way, the other characteristics are the low profile, the potential light weight, the potential low cost, the potential conformability with mounting structure, easy integration in a planar circuit and can have linear elliptic or circular polarisation.

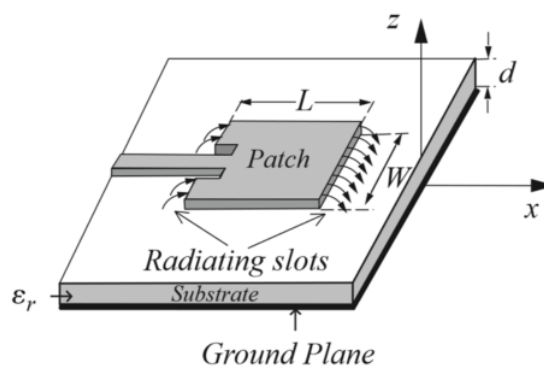


Figure 2.8: Illustration of a microstrip patch antenna [11].

2.3 Types of implementations

In order to develop beyond state of the art, we set to explore antennas outside the realm of the PCB implementation. Different approaches were considered during this study, some of the technologies analysed were: metallic structure, flexible PCB, conductive ink process antennas or laser direct structuring.

2.3.1 Metallic structure

A metallic structure was thought as an external component like a capacitor or a resistance. This component could introduce some advantages, the most valuable advantage is the production process, which is simple and quick, the fact of this structure may be assembled directly onto the PCB since that external connection is not needed is another advantage. Other considered to be advantages are that it is simple, low cost to introduce on the production line, high efficiency and high average gain. On the other hand, they are quite expensive, have low bandwidth, could have higher dimension and their resonance frequency and radiation performance are dependent on the PCB dimensions [12].

A metal antenna can have different designs, as monopole, dipole or IFA, in order to be small typical it is an IFA.



Figure 2.9: Metallic antenna that could be assembled on PCB [13].

2.3.2 Flexible implementation

Flexible substrates are used in several types of circuits nowadays due to the flexibility and liberty to experience different locations and forms. Having in mind that these circuits are really thin they can be embedded inside the cluster or even between the glass and the housing. With the objective of implementing this technology two options are available, the rigid-flex circuits or the utilisation of the FPC/FFC connector that will make the connection between the flexible PCB and the cluster main board.

A rigid-flex circuit is composed of a normal PCB and a flexible PCB incorporated, with the same number of layers and able to make the transition without any losses. However, this is a very expensive technology.

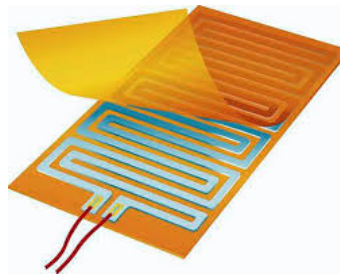


Figure 2.10: Example of a flexible circuit[14].

On the other hand, the second option looks much more attractive costwise. Since that this technology works properly with the display and the PCB, it could be a possibility for this antenna. If this antenna was incorporated with the existent flex it will not represent another process on the production line.

Parameters as gain and efficiency will depend greatly on the antenna structure, placement and surrounding materials.. However, these types of antennas are already included in several different types of products with a good performance. Such as, typically and too much used nowadays, to make connections [15] but also in the innovation and in new implementations, such as an transistor designed to be built and perform with flexible material [15].

2.3.3 Conductive ink process antenna

In a simplest definition this technology is a painting of a pretended shape on a substrate. The conductive ink process antennas appears like a good alternative to integrate above nonstandard materials, such as glass or textile. One printed antenna can be integrated through several processes, inkjet-printing, screen printing, gravure or chemical processes.

The biggest advantage of this printed antenna is the possibility of printing on curved or planar surfaces to make conformal antennas [16]. Typical it is small, easy to manufacture and to integrate. However, generally it is difficult to obtain high polarisation purity, the bandwidth is narrow and the efficiency is generally lower due the dielectric losses.

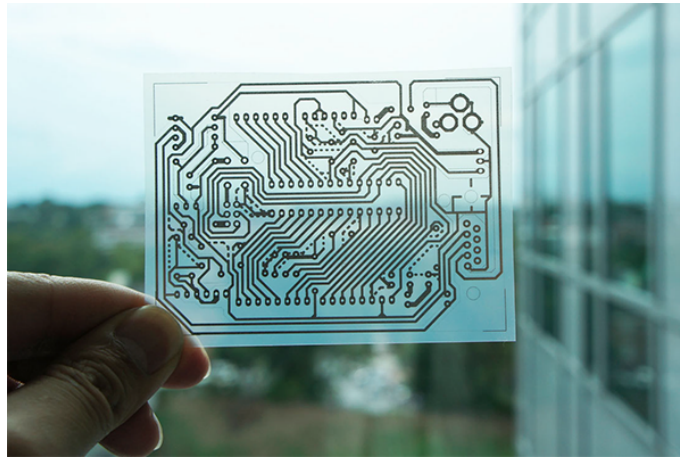


Figure 2.11: Example of a printed circuit using a desktop printer[17].

2.3.4 Laser Direct Structuring

LDS presents as a new technology capable of make electronic circuit, in a non-conventional format, through a plastic substrate. This methodology is already a certainty since that is utilised in several simple applications such as sensors, antennas for cell phones, car applications, etc. The biggest improvement that this technology can offer is the 3D implementation.



Figure 2.12: Example of an LDS automotive implementation [18].

To obtain this antenna some processes need to be done, firstly the plastic that will be utilised in the injection molding should have a special LDS additive, then the laser will expose the conductive part that has been injected, and activate the additive present in the plastic. The next stage is the metallization that consist in a bath with conductive materials, this material will fill the traces created by the lasers and turn it conductive. To finalise, it can be important to assembly some components of this structure, so soldering can be made as an end process [19].

Antennas that are built with this technology are capable to easily provide an efficiency higher than 50% [20].

2.4 Summary

In Chapter 2 several topics have been studied. Because it is important to get a deep understanding on the addressed topics, some fundamental parameters were exposed. Furthermore, the chip antenna which is considered to be the actual project implementation was analysed. Finally, in the last section, some different technologies were observed too.

Chapter 3

Antenna considerations

This Chapter will make a detailed overview about dipole antennas, on section 3.1, and specifically about IFA on section 3.2.1. Furthermore, the matching impedance is explained on section 3.2.3.

3.1 Dipole Antennas

As shown in the previous chapter, dipole antennas are one of the most used and simple type of antennas. The dipole antenna type could be implemented utilising a simple wire and having the feeding point at the center of the wire. The half-wave dipole antenna is the simplest of them. The antenna wire has a total length of half of the resonance frequency wavelength. The name of this implementation is correlated with the frequency and the size of the wire, so, this implementation can reveal to be impossible for small devices with low frequencies. Additionally, its impedance can be predicted by the behaviour of voltage and current. As this antenna has a known behaviour, the impedance at the pretended frequency should be minimum, since there the voltage is minimum and the current is maximum [11]. As shown in Figure 3.1.

As occurred in the half-wave dipole, the monopole antenna lies inside of the dipole category. In a basic explanation, a monopole represents half of a dipole, having half the size of a half-wave dipole antenna consequently the wire is a quarter of wavelength. This antenna have two

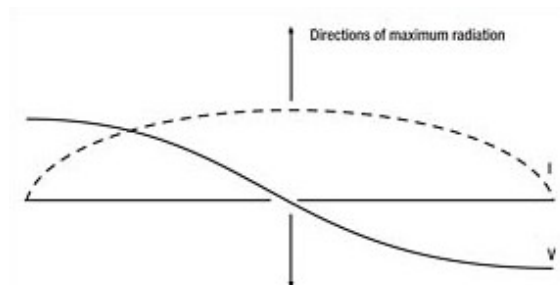


Figure 3.1: Illustration of a half-wave dipole antenna, with reference of current and voltage behaviour.[21]

extremities, one must be open while the other is connected to a signal source with reference to ground plane. The ground is an important part of this antenna and should be at least a quarter of the wavelength in width. The length of this monopole can be reduced, but in order to maintain resonance at the pretended frequency, an inductor near the ground should be added to compensate the capacitive reactance.

The current on monopole has the same behaviour as the upper half of a dipole with the same length. However, the voltage is half of the described on the dipole. This happens because the gap width of the input terminals is half of the one in the dipole, and the same electric field over half the distance can be translated in half the voltage [22]. With that in mind, it can be stated that the monopole impedance is half of the dipole impedance.

To decrease this dimensions, some variations of monopole have appeared, such as Inverted-L antenna (ILA) and IFA, that have this names because they remember, respectively, one inverted L and F .

A ILA, which is a bent monopole, having the radiation closer to the ground, will have a lower radiation resistance, hence changing ILA input impedance. To match the input impedance of an ILA, by manipulate the distance to ground or add a matching network.

If we look at ILA as an evolution of the monopole, the IFA is an evolution of the ILA. In order to design the IFA, relatively to the ILA, a shorting stub is added between the first end of the radiator and the ground plane, as shown in Figure 3.2.

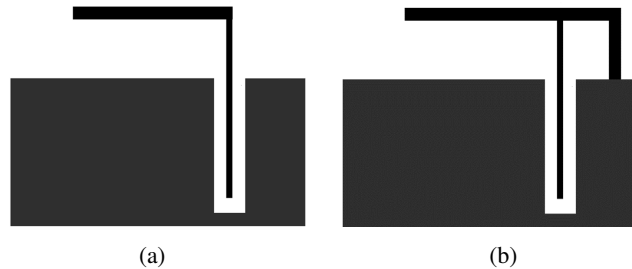


Figure 3.2: Monopole different implementations (a) ILA; and (b) IFA.

3.2 Inverted-F antenna (IFA)

An IFA, has the same length as a monopole, being for that reason possible to design with a total of a quarter of the wavelength. This antenna has a vertical polarisation and the radiation pattern is roughly doughnut shape. The performance of an IFA can be affected by several factors, where join factors like the size of the ground, the dielectric constant, antenna size and antenna position[12].

This IFA has a short arm, described in Figure 3.3 as h_1 , that connects the upper arm, in Figure 3.3 as h_2 , to the ground. It is also possible to observe the feed that makes the connection between the upper arm and one transmission line or even to the rest of the circuit. To correctly implement an IFA, some steps should be followed [10]:

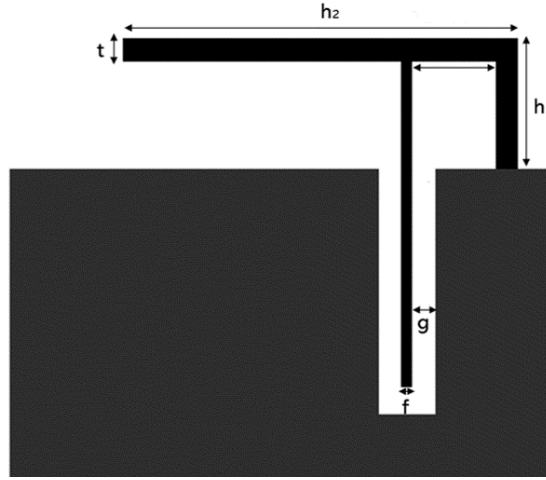


Figure 3.3: Illustration of a IFA.

- The feed is placed from the ground plane to the upper arm of the IFA;
- The upper arm of the IFA has a length that is roughly a quarter of a wavelength;
- The upper arm is shorted to the ground plane;
- The feed is closer to the shorting pin than to the open end of the upper arm;
- The ground plane should be at least as wide as the IFA length and $\lambda/4$ in height;
- If the height of the ground plane is smaller than the IFA length, then the bandwidth and efficiency will decrease.

A IFA allows a greater impedance match, through the distance between the radiator element and the ground, as well as the length and thickness of short stub.

3.2.1 IFA dimensions

The most important dimension of the IFA is already defined, when the length of the monopole was achieved. However the environment where the antenna is inserted plays an important role on this. In this way, some constraints relatively to the space where taken. To IFA implementations was defined as maximum area $30\text{ mm} \times 30\text{ mm}$.

Because of that, the monopole dimensions for the pretended frequency can be determined through the equation-3.1. Taking into account the figure 3.3:

$$h_1 + h_2 = \lambda/4 \quad (3.1)$$

$$\lambda = v/f_r / (\sqrt{\epsilon_r} 4 f_r) \quad (3.2)$$

$$h_1 + h_2 = c/(\sqrt{\epsilon_r}4f_r) \quad (3.3)$$

$$h_1 + h_2 = 30.6\text{mm} \quad (3.4)$$

3.2.2 Feed dimension

In order to ensure that the impedance matches the feed, it should respect some characteristics. The feed is placed from the ground plane to the upper arm of the IFA [23]. This element should in space be closer to the short pin h_1 than to the open end of the h_2 , as previously observed. Since this feed will pass through all the flexible board until the connector, it is necessary for the line to have 50Ω of impedance. This would allow for losses reduction, mainly because all the circuit is matched for 50Ω . Coplanar waveguide with ground was the type of line chosen because is the one that offers better performance and makes more sense, since the ground dimensions are a susceptible parameter.

$$Z_0 = \frac{60\pi}{\sqrt{\epsilon_{eff}}} \frac{1}{\frac{K(k)}{K'(k)} + \frac{K(kl)}{K'(kl')}} \quad (3.5)$$

Through equation 3.5, knowing that the pretended impedance is 50Ω and that the ϵ_{eff} can be determined using the dielectric constant of the substrate, all the other parameters can be found. Analysing equation 3.5, the function $K(x)$ represent the complete elliptic integral of the first kind and its complement [9]. Yet, the k , k' , kl and kl' are defined by the track width, the track of the gaps and the thickness of the substrate.

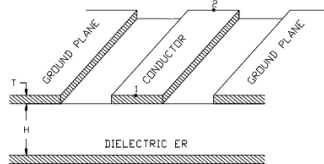


Figure 3.4: Example of a section of coplanar waveguide with ground [24].

Considering as substrate thickness $125\mu\text{m}$, feed thickness 0.12mm and dielectric constant of the substrate of 3.5 it was achieved a width of 0.32mm to the feed.

As, some other dimensions are in fault, some studies were done, tacking in account that $h_1 + h_2$ may be 30.6mm (equation 3.4) the feed have a width of 0.32mm and a thickness of 0.12mm , all of the other values will be analysed in order to take some advantage of that.

3.2.2.1 Stub length tunning effect

Since this board has a dimension of approximately $30\text{mm} \times 30\text{mm}$, considering the previously defined feed, and a width of the arm of 1mm some different extensions of the length were simu-

lated in CST, with the purpose of selecting the best approach at return loss level. On figure 3.3 the sum $h_1 + h_2$ have always been 30.6 mm, however the extension of the h_2 changed. This will alter with the distance to the ground and change the impedance, but also to the bandwidth. This occurs because the variation of the dimension h_2 , move the upper arm away from the ground and, as a consequence the parasitic capacitance effect decreases and the impedance will change.

The thickness of the arm was defined as 1 mm and the distance between the feed and the short arm was 2 mm.

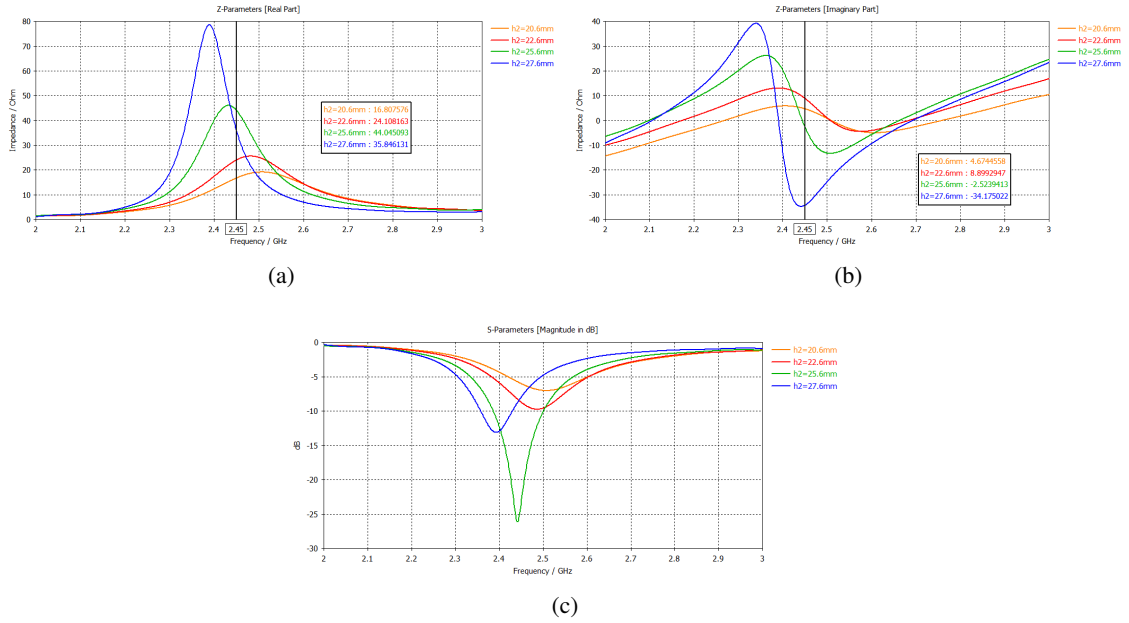


Figure 3.5: Comparison of simulated results of IFA for different lengths of h_1 and h_2 , but maintaining the sum of $h_1 + h_2$ equals: (a) real impedance chart; (b) imaginary impedance chart; and (c) return loss.

Through the analyses of the return loss and the real and imaginary impedance plots, in Figure 3.5, it shows that the compromise between the length of the arms h_1 and h_2 should be ensured. In this parametric study, the perfect match between the shorting stub and the upper arm are achieved when $h_2 = 25.6$ mm and $h_1 = 5$ mm as shown in the impedance plots. Since, the real impedance is close to 50Ω and the imaginary impedance around zero.

The small variation of the resonant frequency to lower values occurs because of the decreasing length of the stub, which change the parasitic capacitance. Another effect that changes the resonant frequency is the length of the feed that increases with the increasing of the stub.

3.2.2.2 Arm thickness tuning effect

Identically to the parametric study done on section 3.2.2.1, a study on the influence of the arm thickness was performed. In this case, the length of h_2 had 25.6 mm and the distance between the feed and the short arm h_1 was 2 mm.

As observed in Figure 3.6(b), at the desired frequency the imaginary impedance will have almost the same value for the different thickness, close to the zero. As occurs to the real impedance that have values around 50Ω . Although the similarity between the values, the lower thickness allows a better impedance match and consequently a fine adjustment of the input impedance of the antenna, as well as has a slight influence on the obtained bandwidth. As shown in Figure 3.6(c).

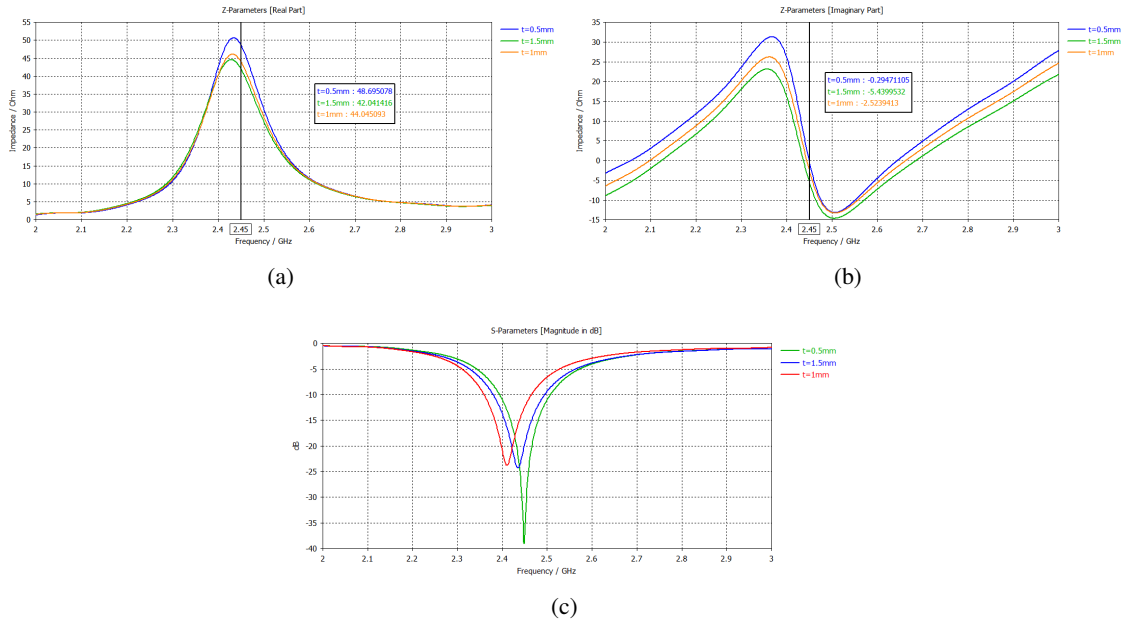


Figure 3.6: Comparison of simulated results of IFA for different thickness of the arm : (a) real impedance chart; (b) imaginary impedance chart; and (c) return loss.

3.2.2.3 Short to feed distance study

Lastly, only one distance value is still unknown. This is the gap between the short arm h_1 and the feed, as saw in the previous section 3.1, this will certainly have a strong influence on the antenna impedance. For this parametric simulation, the upper arm, h_1 , was defined as having 25,6 mm and its thickness was 1 mm.

Starting this analysis for the antenna impedance, Figure 3.7(a) clearly shows that when raising the distance to the feed, the real impedance value increases, until be almost optimum for $s = 3\text{ mm}$, however similar to $s = 2\text{ mm}$. Already, the imaginary impedance values have a major difference, being at 2.45 GHz matched to $s = 2\text{ mm}$. This is reflected in the return loss that are matched for the previous distance, as shown in Figure 3.7(c).

3.2.3 Impedance Matching Network

In the previous section 3.2.1, IFA dimensions were analysed using the antenna tuning. As shown in section 2.1.10, a process to make the matching of impedance. A matching could be done externally to the antenna, using a matching network. This consists in a simple circuit with lumped

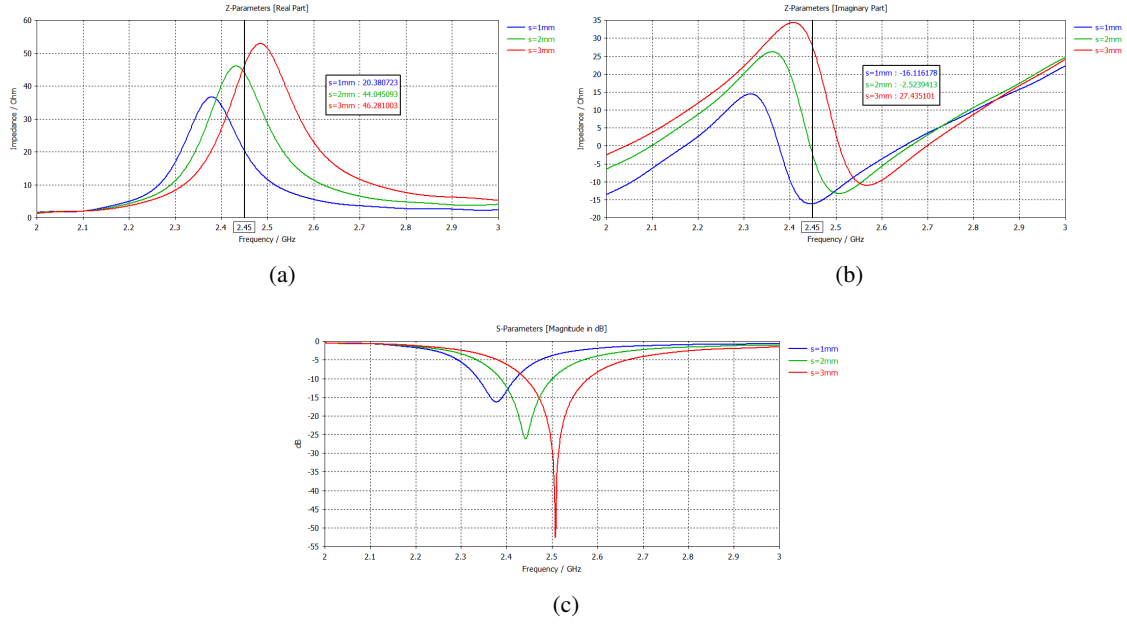


Figure 3.7: Comparison of simulated results of IFA for different distances between the short stub h_1 to feed : (a) real impedance chart; (b) imaginary impedance chart; and (c) return loss.

elements.

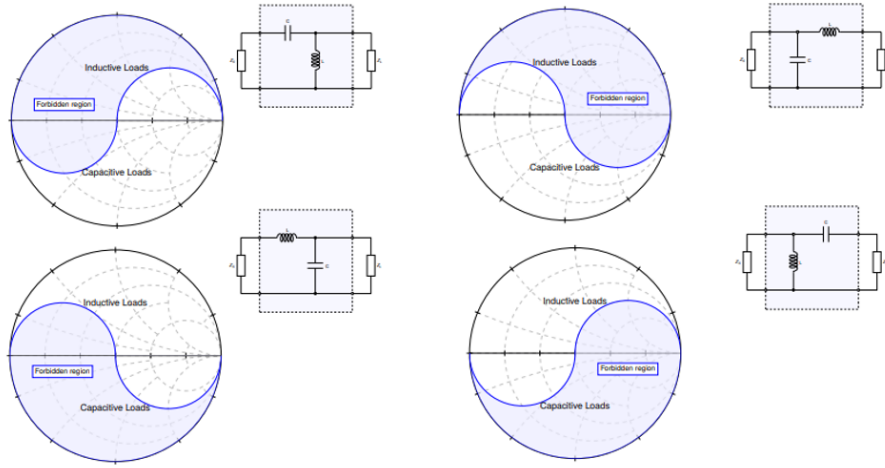


Figure 3.8: Location of the load on Smith-chart and respective impedance matching network[25].

An impedance matching network is necessary when the load is different from the pretended impedance value. When this occurs, an impedance matching network is required to ensure most of the power from the Radio Frequency (RF) source is delivered to the load [26]. In this way, it is pretended to match the complex source impedance in order to turn the load one the same as the characteristic impedance, implementing a matching network near the load. As all the impedance values, except when the load is open or short, are possible by matching through inductors and ca-

pacitors. The Smith chart is used with the main goal to understand where the load is and help with the maths that realise the matching. The most common matching networks are the L-Matching Network and the Pi-Matching Network. In this work, the L-Type will be used. It is composed by two lumped components, a shunt and a series element. For each specific location of the load on the Smith Chart corresponds to one specific circuit configuration, as shown on figure 3.8.

To design the matching network, some steps need to be done. Firstly, the load impedance needs to be marked on the Smith Chart and there the topology will be selected. Then, the load will be moved along the constant resistance/conductance circle until achieving the unit conductance/resistance circle. This will result in the value of the L or C. As a last step, the load moves along the resistance/conductance circle until the origin, where the C or L value is determined. Where the shunt element has as function rotate the point to achieve the real part equals to 50Ω and the series element turns the imaginary part null.

3.3 Summary

In this Chapter some important considerations were taken. Starting with the concept of a dipole antenna until the achievement of a successfully built IFA 3.1. Then, IFA dimensions were calculated and a parametric study was done in order to understand how to take the maximum advantage of that type of antenna 3.2.1. Finally, a impedance matching network was analysed. This enabled an understanding on how the matching could work.

Chapter 4

Antenna Design

In this Chapter 4 all the development of the work is covered. In section 4.1 the proposed solution is introduced, being analysed all the possibilities in detail. Then, section 4.2 addresses the IFA and the material surrounding the antenna. On section 4.3 the design and development of the IFA is analysed, this section is supported by the chapter 3. In section 4.4, the integration of the antenna on the device is studied. Concluding, section 4.5 specifies how final model is achieved and the layout determined.

4.1 Proposed Solution

In order to start the work development, all section 2.3 previously studied typologies were compared. So, with the objective to find the best possible integration ability, the available space was observed in order to be possible to develop there an efficient antenna.

In this way, the space that has been considered available was the space inside the housing. Hence, the PCB was inserted between the display and the housing, where despite the minimised space some antennas could work. This is depicted in Figure 4.1.

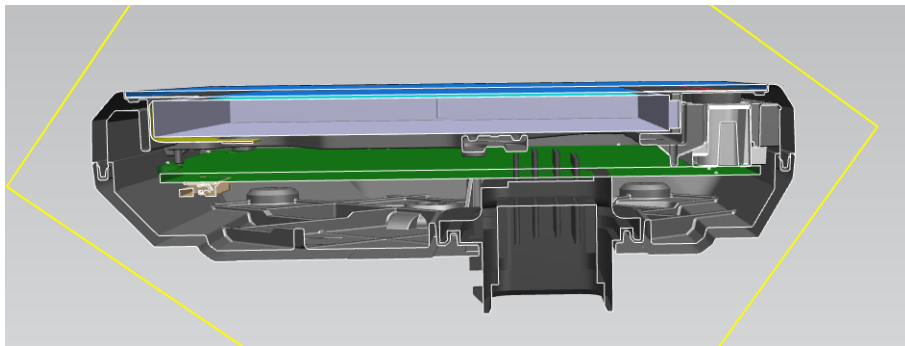


Figure 4.1: Side view instrumentation cluster.

In Figure 4.1, this cluster is composed of several components such as: the housing, the front glass, the display with 2 flexible circuits and respective connectors, the pug, the heat sink, several screws and led's.

Another problem that is important to take care on this project, mainly due the vibration that occurs in a motorcycle, is the connection between the PCB and the antenna. Since that RF connectors had a bad response when suffering vibration, another solutions should be found as well.

Having this in mind, all the studied technologies were analysed for this project in order to comprehend if it could work properly.

4.1.1 Metallic structure

Relatively to space, between the display and the housing this structure was immediately rejected due the required thickness there. However, inside the housing and since that this antenna should be implemented onto the PCB, a lot of space is available, enabling this antenna to possibly be placed on the intended position.

The most valuable advantage is the possibility for this structure to be assembled directly onto the PCB, since that external connection is not needed the interference is eliminated.

On the other hand, in comparison with the chip antennas, the possible improvement of both efficiency and cost is not good enough in order to compensate this change.

4.1.2 Flexible implementation

To implement one flexible antenna two options were previously studied, the rigid-flex board that seems the perfect solution (the losses in transmission are almost nonexistent) however it will discard since it is expensive. Another available solution is the use of an FPC/FFC connector, which is already present on the cluster and is ready to perform the connection between the display and the board. Because it uses a flexible PCB, this new alternative does not increase the value of production.

The use of the FPC/FFC connector solves the recurrent problem of vibration existent on RF connection. This technology is a serious candidate to develop this antenna.

4.1.3 Printed antennas

In this work printed antennas could be implemented in two different substrates and consequently in two different spaces. One of them is the frame of the display, the glass that had already a frame of black ink. Returning to this solution the problem of connection will arise, turning this one an undesirable option.

On the other hand, above the polymer that is present in the housing and using as connector one of the four screws presents on the cluster, that start on the back housing and end on the PCB. Therefore, the printed antenna is a viable candidate, the antenna should stay on lateral sides of the housing where the surface is not planar. This results in a manual implementation on the production line which increases manufacturing costs.

	Available Space	Connection to board	Constraints	Conclusion
Metallic Antenna	on PCB	assembled directly	expensive in comparison with with current solution	excluded
Flexible Antenna	all cluster	trough the FPC/FFC connector	depending on FPC/FFC response	viable
Printed Antenna	all cluster	only viable on the housing using the screws	expensive on the production line due the manual process	excluded
LDS Antenna	on housing	through the screws	prototype only available in 2D	excluded

Table 4.1: Comparison of all different possibilities of implementation.

4.1.4 Laser Direct Structuring

LDS has some similarities to printed antennas, however, this technology needs a specific substrate to work. In this way, the implementation of the display was immediately discarded. Still, this could be implemented in the housing by changing the actual material that is PBT-ASA-GF30 to a simple PBT, where LDS may work properly. As for printed antennas, the same solution could be implemented to make the connection between the antenna and the PCB, using the existent screws, like analysed in the section 4.1.3.

Despite that and after looking for some available producers of this technology, this implementation had to be discarded since prototypes are only available in 2D. Which disables the major advantage of this technology.

4.1.5 Selected Technology

In conclusion, after the analysis of previous presented implementation solutions and comparing with the pretended requirements, table 4.1 arose as a summary. Besides, if the FPC/FFC connector supports the connection, the flexible antenna will be the perfect solution.

4.1.6 Selected Antenna

It is clear that based on the studied technologies, it is now possible to select the antenna that will better fit this work requirements. With this information and recovering to section 2.2 and 3.1, the IFA was chosen.

4.2 IFA project

4.2.1 Connector Response

In order to validate the selected technology it is important to analyse if the FPC/FFC connector could support the transmission of RF signals at 2.5GHz with minimal insertion loss, therefore, not hindering the radiation performance of the antenna. A 3D model of the connector was created in

CST and electromagnetic simulation was performance to evaluate it's behaviour and have a first judgement on viability. This software is a specialist tool for the 3D Electromagnetic simulation of high frequency components [27]. It resorts to Finite Integral Technique (FIT) in the time domain, to solve the Maxwell's equations.

In this way, on CST, the flexible circuit board, the PCB and the FPC/FFC connector models were inserted with one transmission line and a port in each board. The magnitude of the S-parameters chart, that represent the insertion loss, is used as the parameter to ensure that this signal will be transmitted without significance losses. This magnitude coefficient graphic shows the reflection power on the input. In this way, the return loss must be at the maximum -10dB and the insertion loss should be minimal (e.g. $S_{21} > -3\text{dB}$).

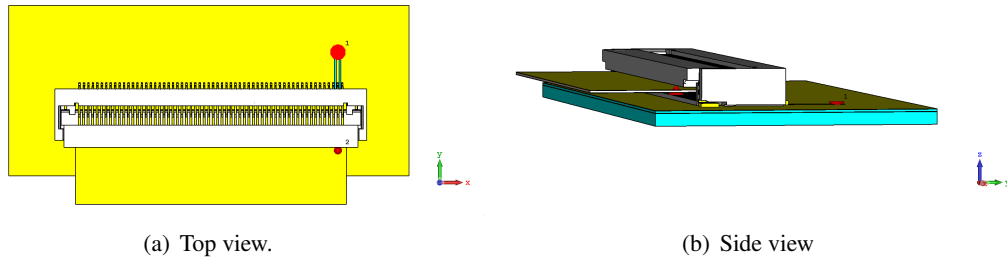


Figure 4.2: Connector, flexible and PCB models in CST

As shown in Figure 4.3 until 3 GHz any information can be passed through the connector with a good performance. Additionally, it is noticeable that S_{11} value is around -13.92dB where as S_{12} is approximately -0.79dB . These values are in accordance with the requirements. Therefore, this connector can be a solution for this work .

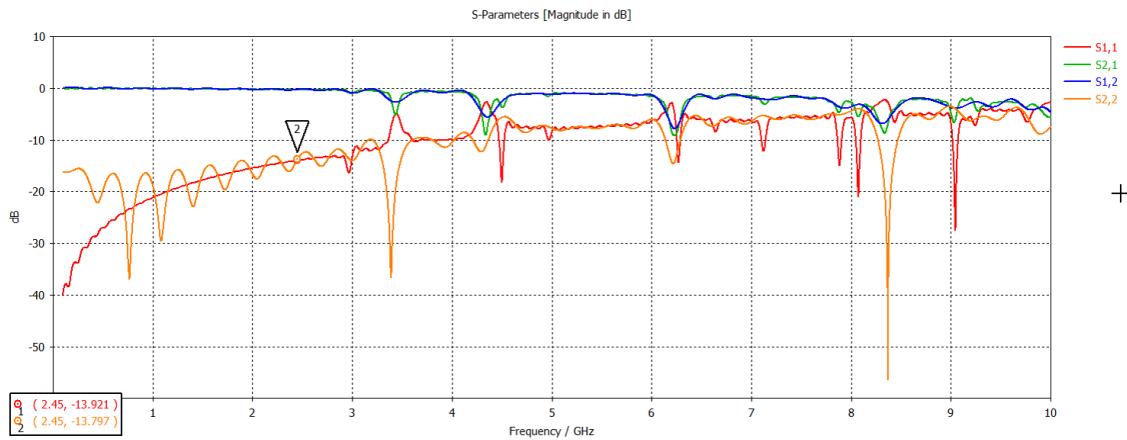


Figure 4.3: Connector simulation response.

4.2.2 Antenna Material

Now that the implementation and the type of antenna are explained, it is important to define the materials that will be used in order to define and design the pretended antenna. So, for the flexible antenna, the substrate material will be polyimide, more precisely kapton, that is available in different thickness depending on the supplier. Along this chapter and for simulation effects, the considered thickness will be $125\text{ }\mu\text{m}$ with a dielectric constant of 3.5 and a dissipation factor of 0.0026. The radiating element will be built in copper as well as the ground.

Knowing that this line will be responsible for the connection between the antenna and the PCB, it is crucial better understand the FPC/FFC and its dimensions.

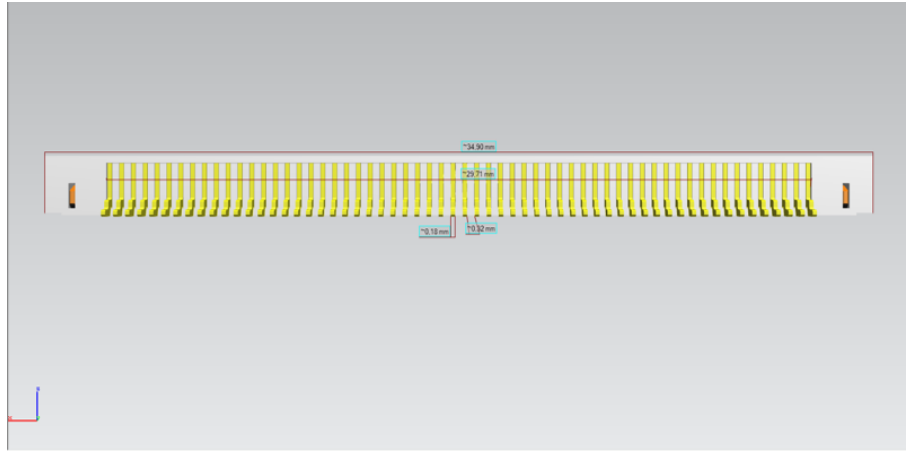


Figure 4.4: Connector simulation with some measurements.

The width of a single pin is 0.18 mm, as can be observed in Figure 4.4, and the gap between the pins is 0.32 mm. In this way, the width of the line should not occupy more than one pin. Thus, with the thickness of $125\text{ }\mu\text{m}$ and a wanted impedance of $50\text{ }\Omega$ the track width should be 0.32 mm and the gap width 1 mm.

4.3 Antenna Design

As analysed on section 3.2.1, $h_1 + h_2$ should be approximately 30.6 mm. In the first simulation model, h_1 will be 5.0 mm and consequently h_2 equal to 25.60 mm. In this simulation only the flexible antenna will be studied 4.5.

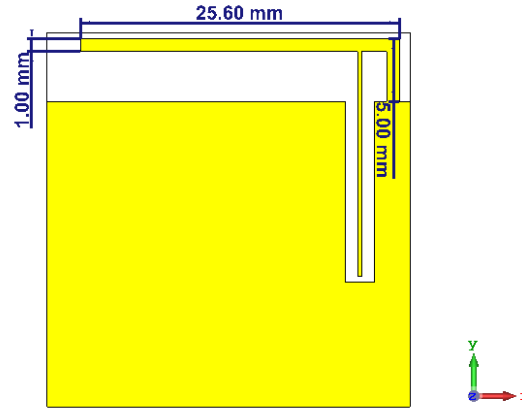


Figure 4.5: Flat antenna and most important dimensions.

For simulation purposes, the reflection coefficient considered as parameter of acceptance will be -10 dB. The bandwidth of interest will be understood between 2.4 GHz and 2.5 GHz to cover the Bluetooth and Wi-Fi bands. As observed in Figure 4.6 all the pretended bandwidth is covered. Antenna impedance is $45.29 + 2.23j\Omega$, that will not need of a matching circuit because this antenna impedance is close to 50Ω , that is the characteristic impedance.

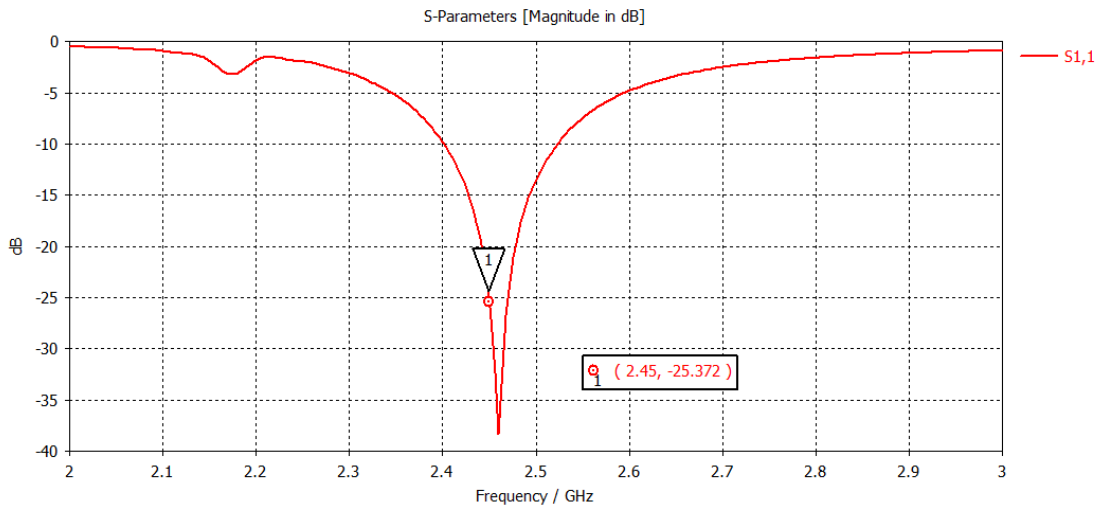


Figure 4.6: Results of reflection coefficient of the simulated antenna on CST.

Other important characteristics of an antenna are the efficiency and the radiation pattern. In this simulation, the antenna shows at 2.45 GHz a total efficiency of -0.165 dB is delivered. This means that more than 96 % of the power at antenna input is radiated. As predicted, the radiation pattern reassembles a doughnut shape.

Before introducing this antenna on the PCB and the FPC/FFC connector, the feed of the IFA should be extended until the end of the substrate, where the antenna will join the FPC/FFC connector. This step will increase the stub that start and ends at the substrate extremity. So, in Figure 4.7, this exchange is shown.

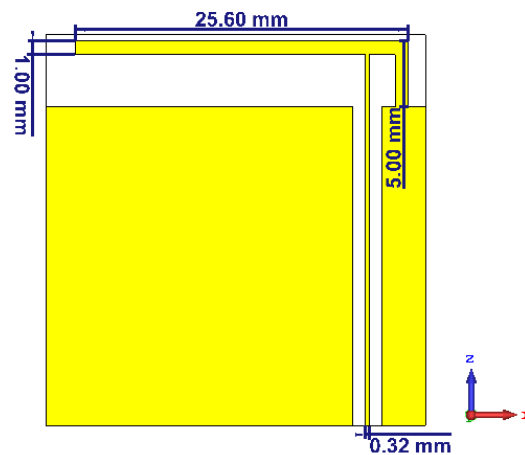


Figure 4.7: Flat antenna with complete feed and most important dimensions.

in Figure 4.8, the comparison between this model and the previous one is made. If some attention is given to the smith diagram of the two antennas, the effect of the stub is evident. This occurs because the smith chart of the first simulation screws in turn of the center and result in the new load position.

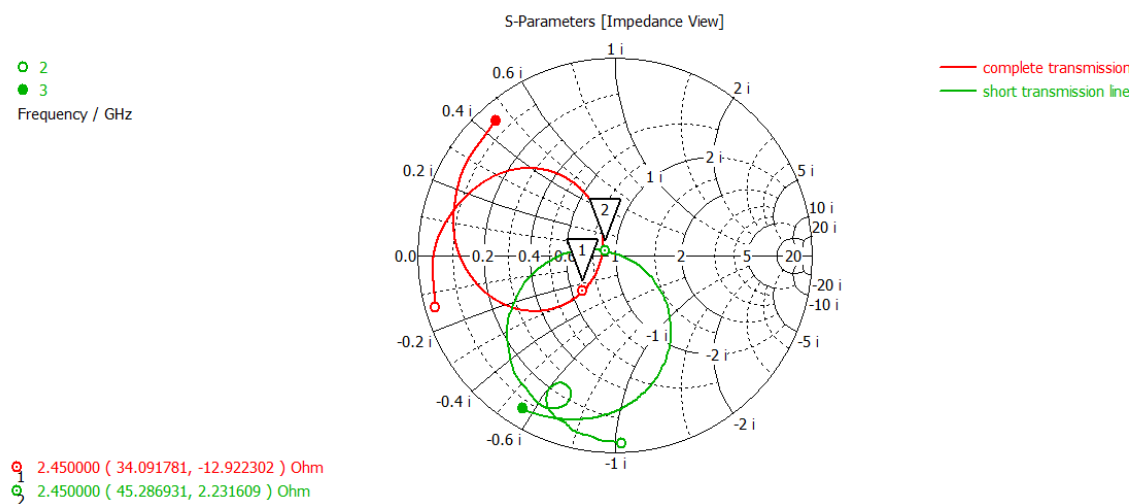


Figure 4.8: Flat antenna comparison with feed different dimensions, through a Smith-Chart.

The increasing stub dimensions justify the decreasing of the return loss from one model to the other, as well the resonant frequency shift, that is present in the s-parameter chart 4.9.

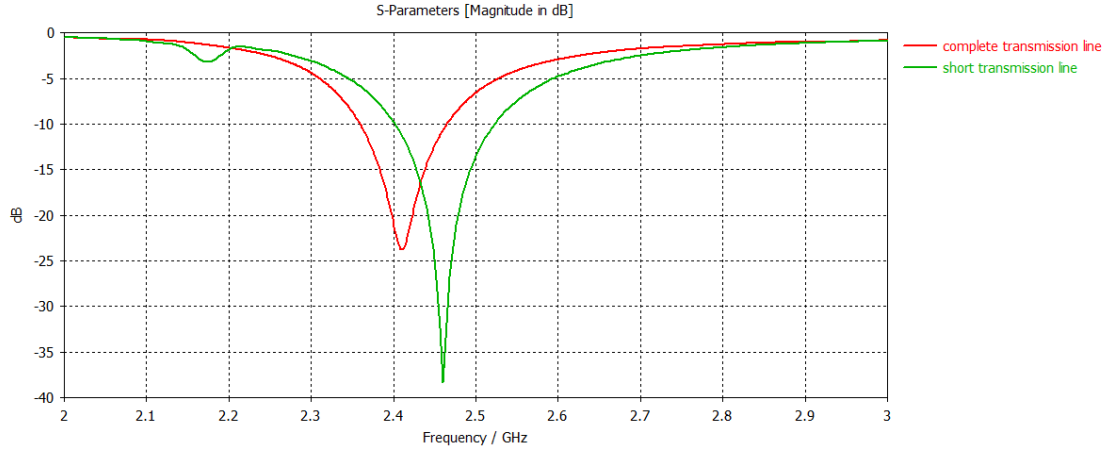


Figure 4.9: Flat antenna comparison with feed different dimensions, through a S -Parameter Chart.

4.3.1 Antenna Design with connector

After completion of the antenna design and correct dimensioning, the flexible PCB with the antenna was integrated with a model of the connector and the rigid PCB to take the whole transmission chain into account. This is shown in Figure 4.10. With this new model of simulation, it will be easier to understand how this connector could support this transition between boards.

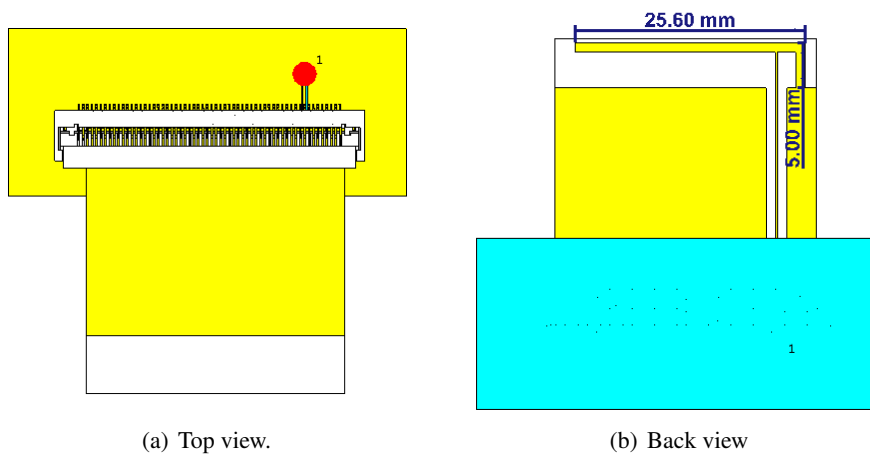


Figure 4.10: Model of the flat antenna on flexible substrate, FPC/FFC and PCB for simulation on CST.

In Figure 4.11 the new reflection coefficient plot depicts some mismatch.

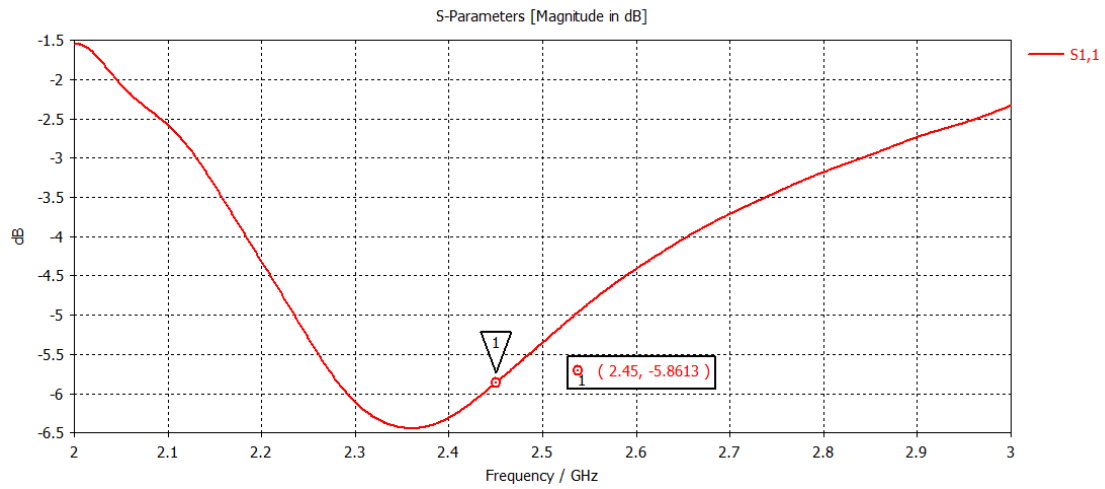


Figure 4.11: Results of reflection coefficient of the simulated antenna, connector and PCB on CST.

This result explains that impedance matching is needed to achieve the requirements. This can be done through one of two steps: A redesign can be done in order to fit the pretended goals; Or a matching network circuit can be included. Because this is a flexible circuit and since that this flexibility could influence the way as this antenna radiates, the matching network will be used in order to improve the impedance match.

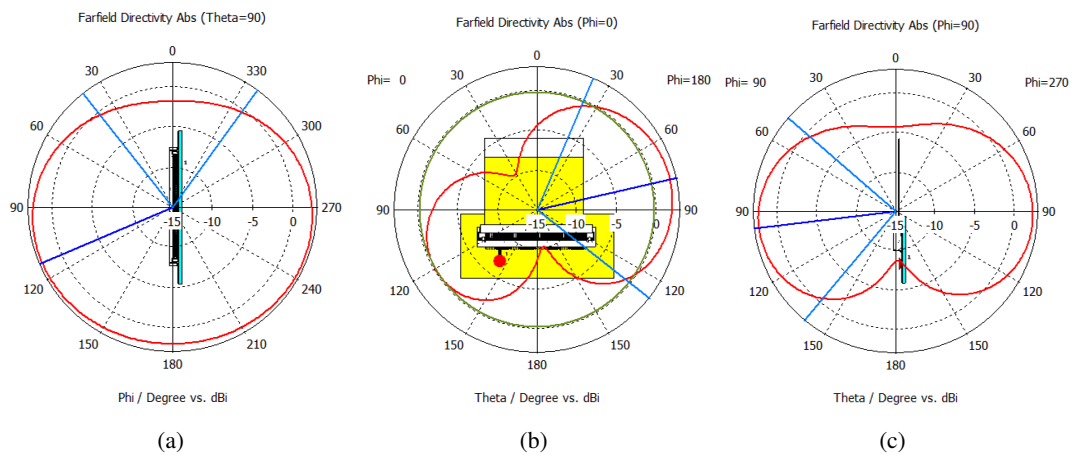


Figure 4.12: 2D radiation pattern of the simulated flat antenna, connector and PCB at: (a) XY plane; (b) XZ plane; and (c) YZ plane.

As observed in Figure 4.12, this radiation pattern is in accordance with the predicted result, a doughnut shape. As shown in Figure 4.13.

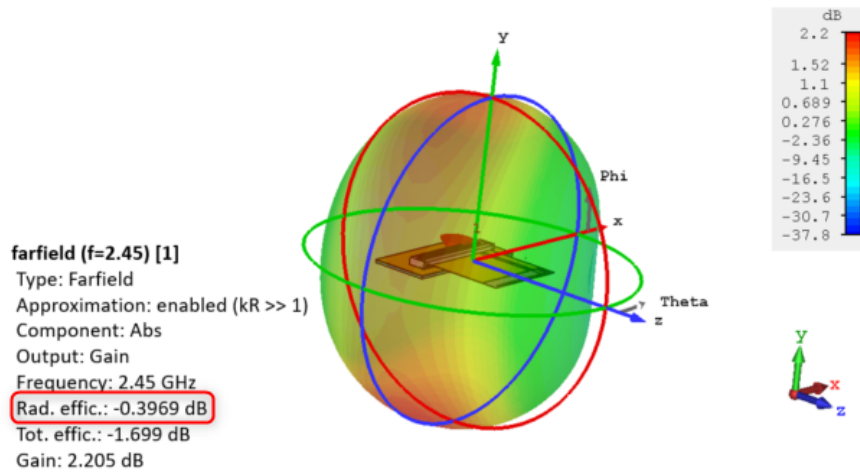


Figure 4.13: Simulation 3D radiation pattern of of the simulated flat antenna, connector and PCB on CST.

4.3.2 Impedance Matching Network

With this model, the impedance of the circuit is $147.41 + 28.3 j \Omega$ being for that reason misadapted. Following the L-type matching network, explored in the section 4.3.2 and having in mind the location of the load, a shunt component followed by a series element starting from the antenna should be inserted, as explained in Figure 3.8. In this case, the circuit chosen was a capacitor in shunt and a series inductor. As in Figure 4.15, the capacitor will move the load along the conductance circle until achieve the unitary resistance circle. From this point, the inductor will move the load along the resistance circle until reaching the characteristic impedance.

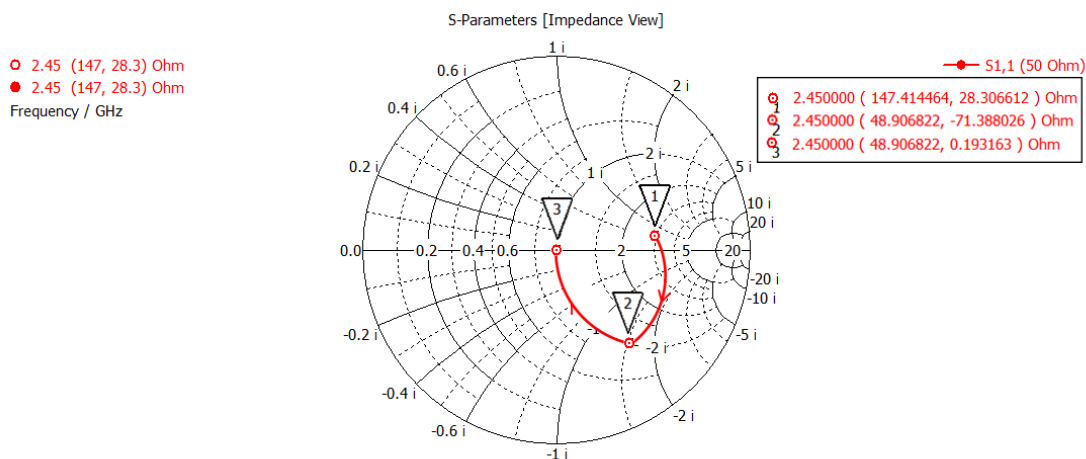


Figure 4.14: Smith chart where the point 1 is the initial point, moves along the arrow until the point 2 where the capacitor was inserted, finally the point 3 located in the final impedance after the insertion of the inductor.

To match this model a capacitor of $0.7pF$ and a series inductor of $4.6nH$ were inserted on CST to improve the result. Where the shunt element has as function rotate the point to achieve the real part approximately 50Ω and the series element turns the imaginary part null. As can be observed in Figure 4.15, adding the capacitor and the inductor shows a favourable result, with an impedance of $48.9 + j0.19\Omega$, as shown in Figure 4.15(a). With the corresponding return loss response in Figure 4.15(b)

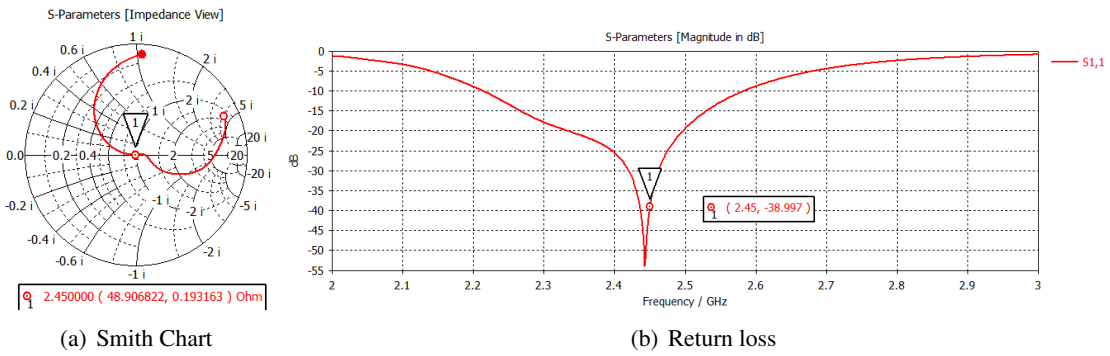


Figure 4.15: Simulation results for reflection coefficient with a matching network circuit, with a capacitor of $0.7pF$ and a inductor of $4.6nH$.

In Figure ?? it is possible to observe that the antenna is a perfect match with the characteristic impedance at the central frequency of the desired bandwidth. However, it is important to consider that this value may change, when inserted in the cluster housing. A simple increment on the transmission line may change the impedance and consequently the values needed for the matching network, as well as the shape that the flexible can take.

After introduction of the matching network, the efficiency of the antenna remains acceptable, in a total of 90%. The radiation pattern remains unchanged.

4.3.3 Folded Antenna

After finishing the design of the whole chain with matching network, transmission line, connector transition and antenna, the antenna was flexed to the potential final assembly position to be considered, in order to fit into the available space on the cluster. This is depicted in Figure 4.16.

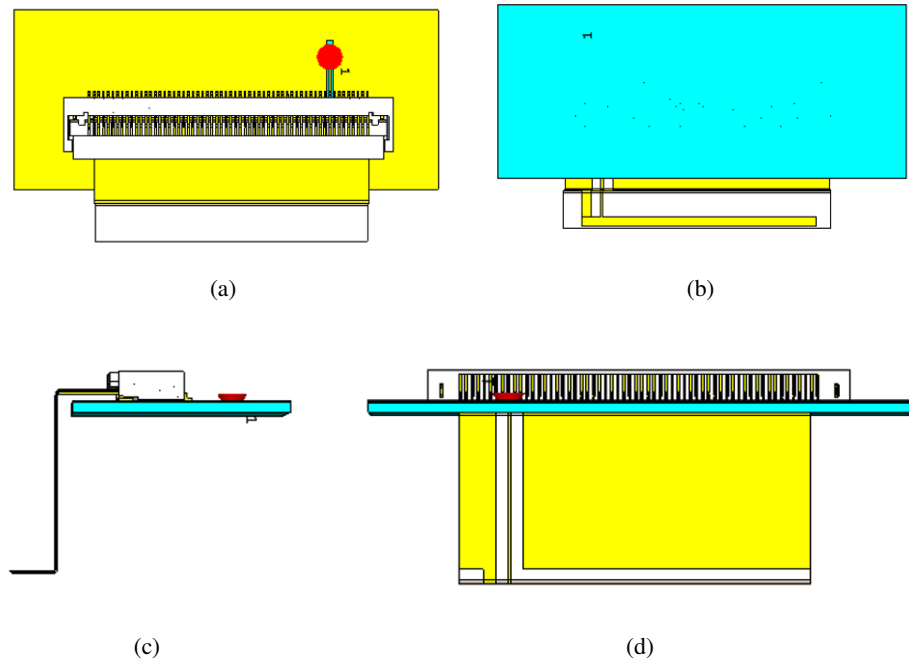


Figure 4.16: Illustrations of the PCB, connector and flexible antenna folded models: (a) top view; (b) bottom view; (c) side view; and, (d) front view.

As expected, when the antenna PCB is folded some differences are noticeable in the antenna parameters, such as resonant frequency, bandwidth and impedance. In Figure 4.17, the resonant frequency changes in comparison with the flat antenna. In Figure 4.17(b) and Figure 4.17(c) the two modes of operation are shown, when the flexible was fold this was evidenced, as the inflections on the imaginary plot shows. The antenna folds can be compared to a decrease of the length of the arm, since the resonant frequency shifts upwards.

The impedance at 2.45 GHz is $88.03 + j25.08\Omega$, thereof, a matching network is needed to achieve impedance matching. The impedance matching network is comprised of a series capacitor of $0.8pF$ and a shunt inductance of $3.2nH$, which will lead to a return loss as shown in Figure 4.18.

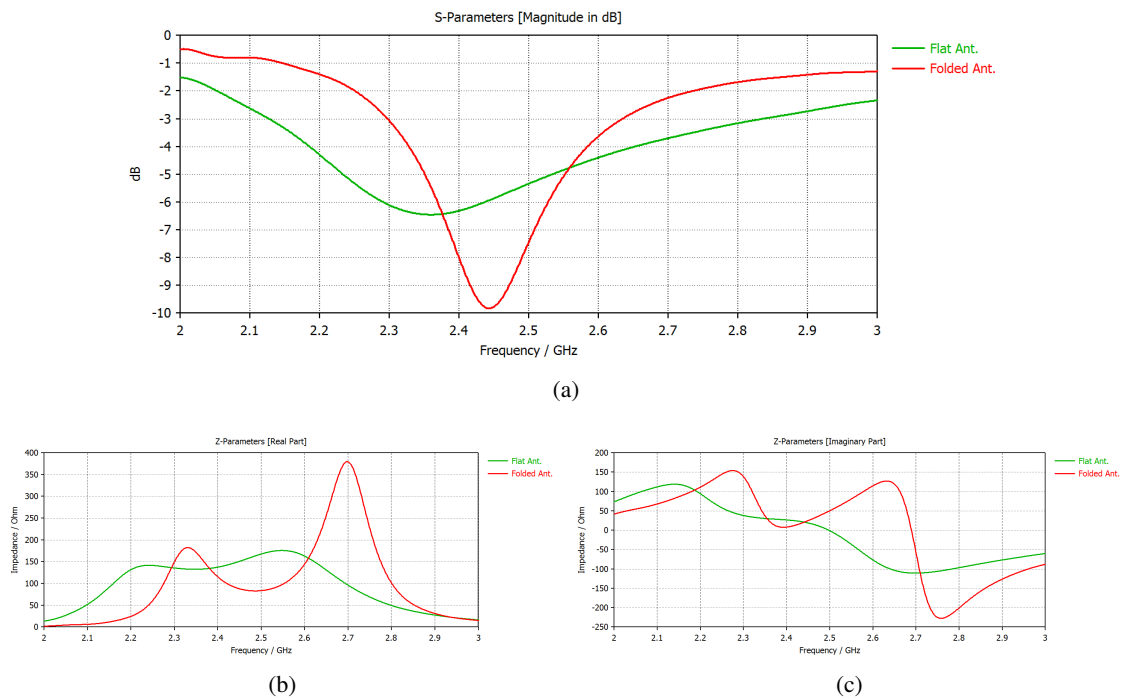


Figure 4.17: Comparison of the flat antenna and folded antenna. Both models have no matching network impedance. Trough: (a) the reflection coefficient; (b) real impedance chart; (c) imaginary impedance chart.

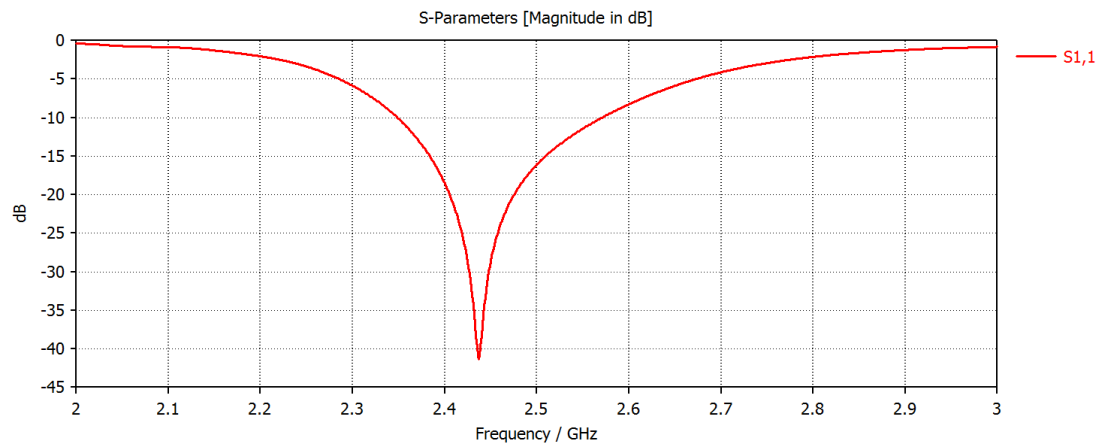


Figure 4.18: Simulated folded antenna with a matching network.

Considering the efficiency, even with the flexed antenna, acceptable performance is achieved, with values above 93 %.

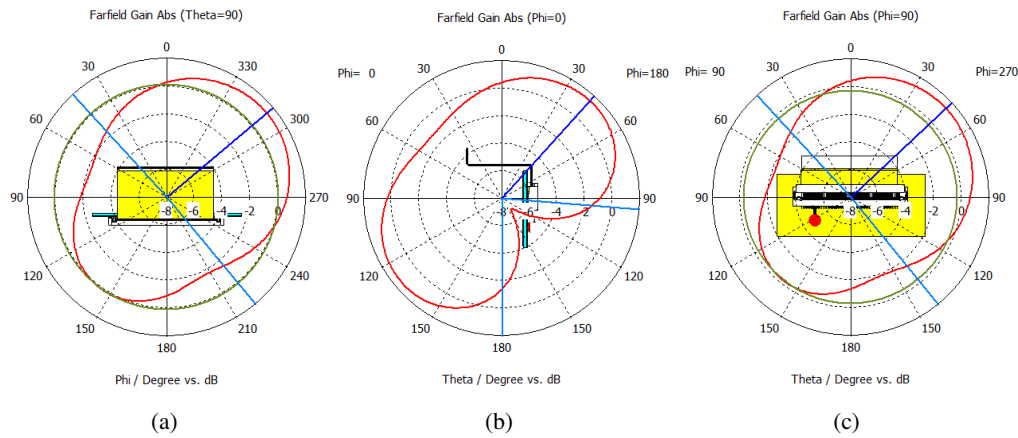


Figure 4.19: Simulated 2D radiation pattern of folded antenna at: (a) XY plane; (b) XZ plane; and (c) YZ plane.

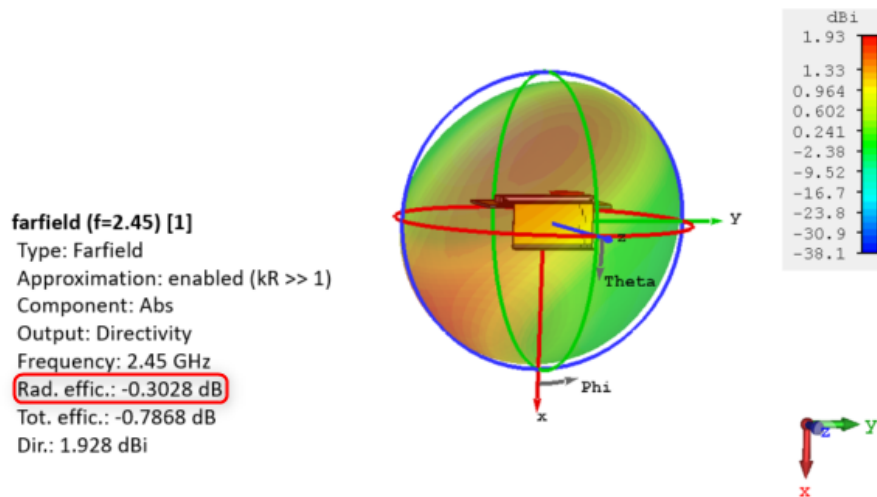


Figure 4.20: Simulated 3D radiation pattern of the folded antenna.

4.4 Integration of the flexible antenna on cluster

As previously mentioned, the housing has several components. The majority will introduce minor effects to the efficient radiation of this new antenna, since they are, essentially, made of polymers or glass (dielectrics with low to moderated losses). However, the display of the cluster has as metallic backcover, which will act as blocker that could decrease the efficiency and distort the radiation pattern. Thereby, to the previous simulation model the display was added with the main goal of understanding if this antenna could behave properly or if some changes would be needed.

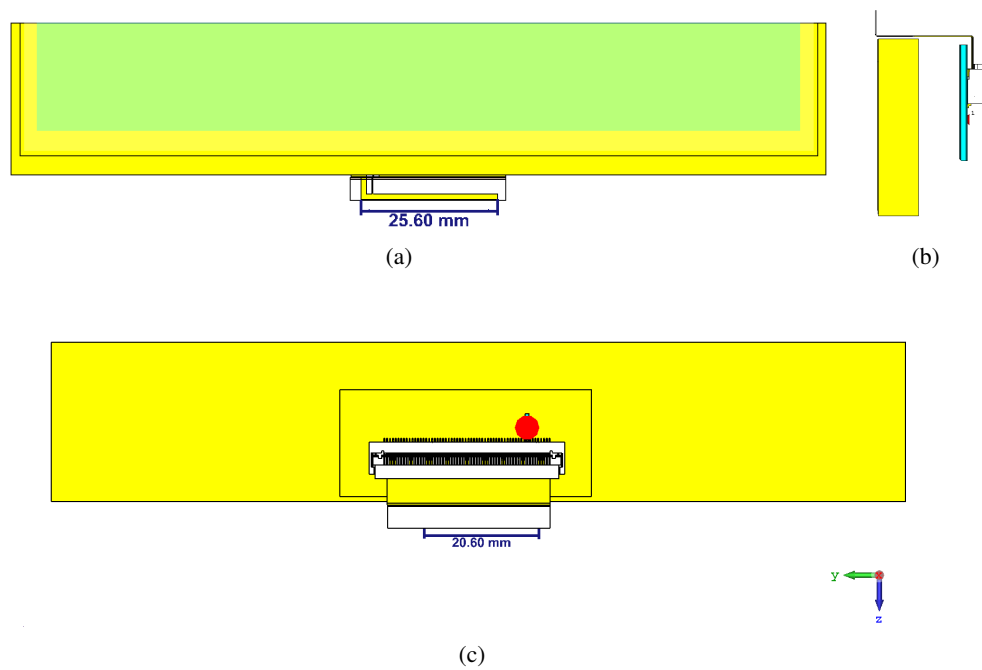


Figure 4.21: Flexible antenna with display models on CST. (a) front view; (b) side view; and (c) bottom.

As expected, the inclusion of a part of display induces some changes on the antenna response. However, the return loss plot of the new model, in Figure 4.22, shows an improvement of the return loss and a small shift of the resonant frequency, when compared to the previous result in Figure 4.17(a).

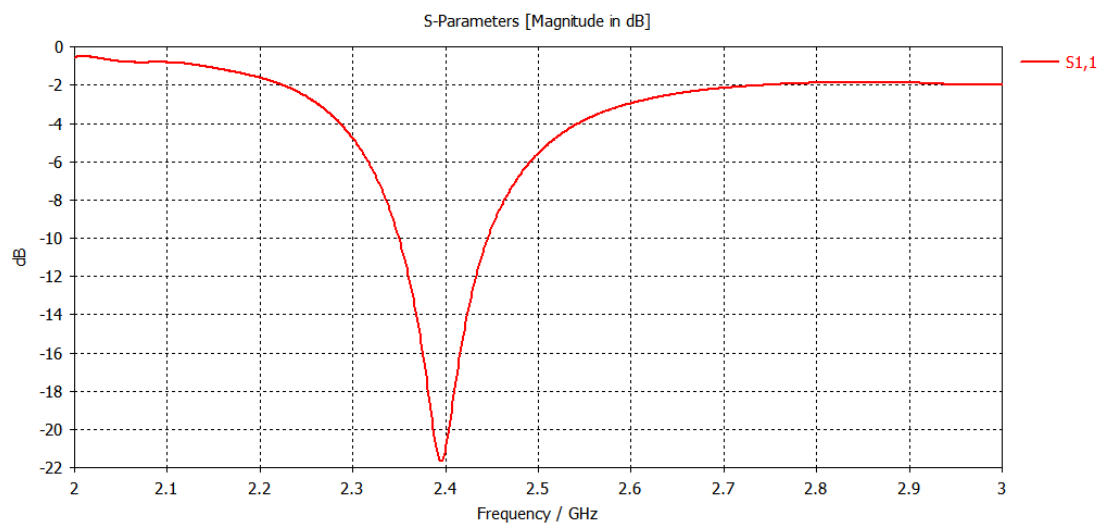


Figure 4.22: Simulated return loss of the flexible antenna model with the display backcover.

The maximum gain to the pretended frequency is 2.493 dBi and the efficiency does not suffer a significant reduction, being the total efficiency, now at 94 %, as shown in Figure 4.24.

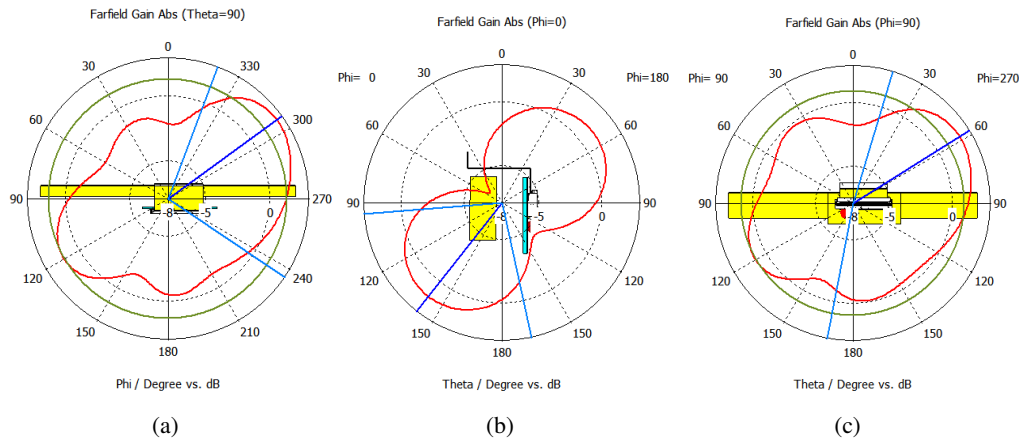


Figure 4.23: Simulated 2D radiation pattern, of the flexible antenna with the display backcover at: (a) XY plane; (b) XZ plane; and (c) YZ plane.

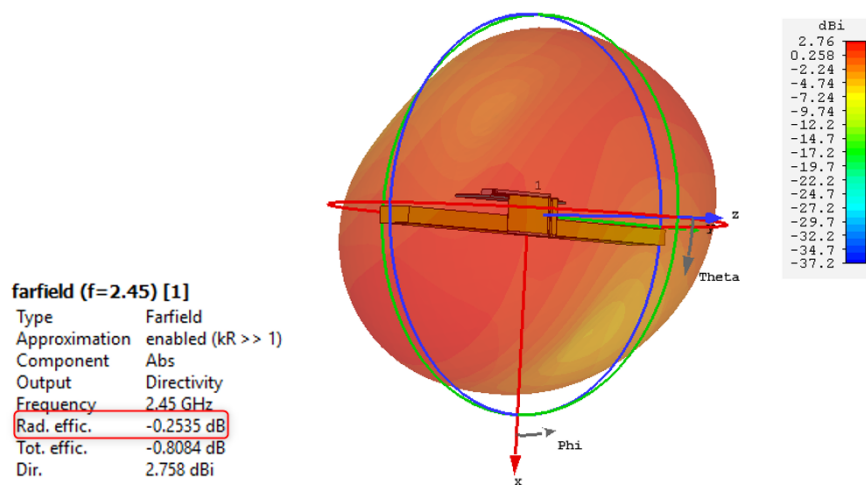


Figure 4.24: Simulated radiation pattern 3D of the flexible antenna with the display.

4.5 Prototyping

The last stage of the work, before the results analysis, was the prototyping phase for this flexible antenna and the PCB. Due to some limitations of production, the thickness of the flexible antenna materials had to be changed. It was necessary to remake the simulations to confirm the results.

Copper Thickness (mm)	Substrate Thickness (mm)	Rad.effic.(dB)	Gain(dBi)
12	0.125	-0.2535	2.758
35	0.085	-0.57	3.601

Table 4.2: Comparison between the radiation proprieties to the both models.

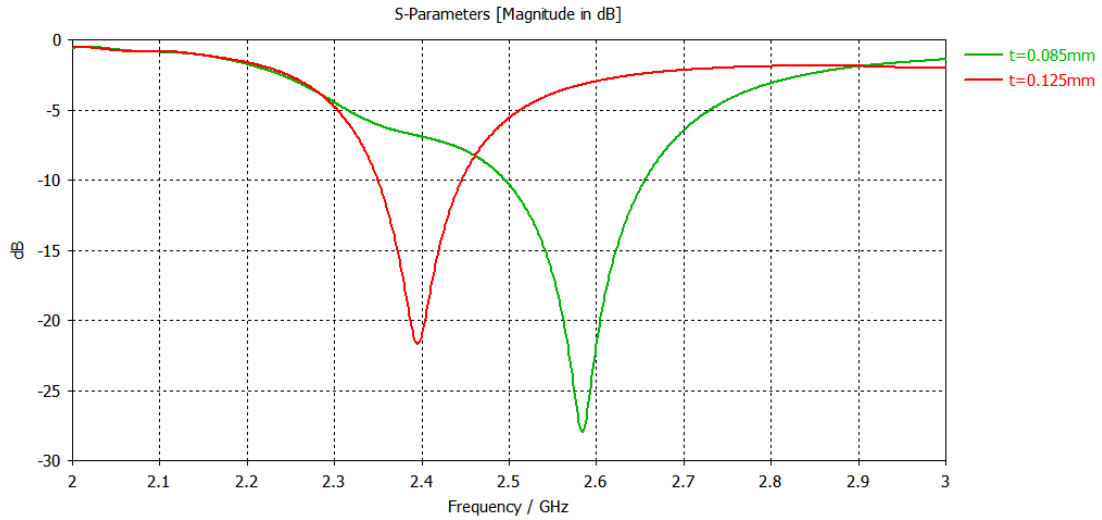


Figure 4.25: Simulated return loss of flexible antenna with display, with substrate thicknesses of 0.085 mm and 0.125 mm and copper thickness of 0.035 mm and 0.012 mm respectively.

After the adjustment of the conductor and substrate as well as the transmission line width, the graphic of the Figure 4.25 make the comparison between the new model and the previous one. The thickness of the substrate and the copper have an influence, in this case, this combination widens the bandwidth, improve the minimum return loss and slightly shifts the central frequency to higher values. Applying an impedance matching network this mismatch can be compensated.

Through the analyses of both models, it is clean that the antenna with corrected fabrications parameters offers a good performance, since that the efficiency is similar and its gain shows some improvements.

4.5.1 Final model

With the purpose of re-turning the central frequency, the upper arm h_2 was decreased and the short stub increased, to obtain the theoretical sum of 30.6 mm. In Figure 4.26, none of them are a perfect solution, however both are strong candidates to work. The impedance of the tuning antenna at 2.45 GHz is $27.4 + 5.68j\Omega$, this can be improved using an impedance matching circuit.

Model	Rad.effic.(dB)	Gain(dBi)	Directivity(θ, ϕ)
Original	-0.057	3.601	(70,334)
After tuning	-0.3167	1.972	(55,14)

Table 4.3: Simulated antenna parameters comparison between the both antennas with display.

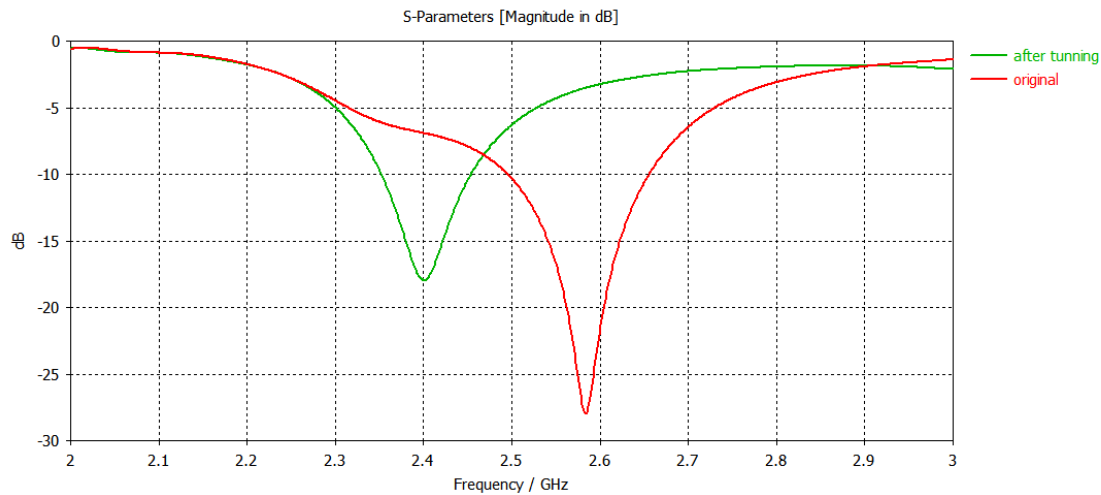


Figure 4.26: Simulated return loss comparison between the both antennas with display.

This model offers a good performance of radiation, with a maximum gain of 1.972 dB, the efficiency is about 94%. in Figure 4.27 and 4.28, this is shown.

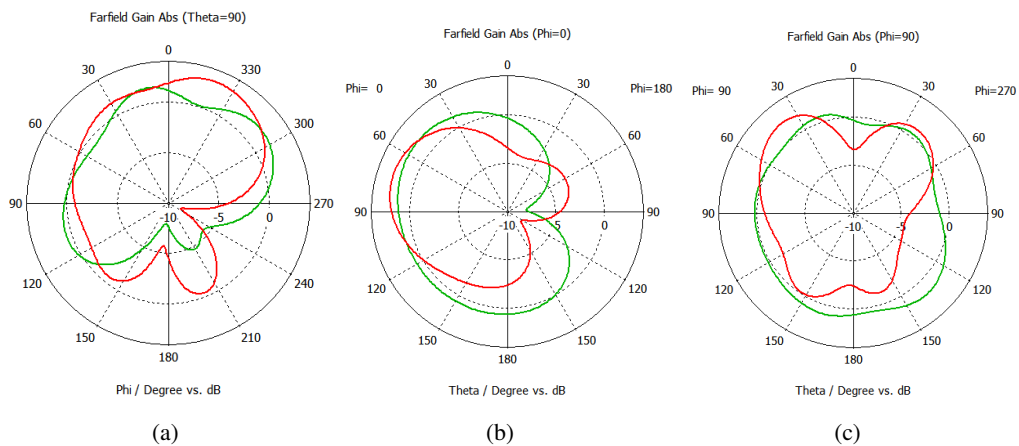


Figure 4.27: Simulated 2D radiation pattern comparison between the both antennas with display, marked in green the antenna after tuning and in red the original antenna at: (a) XY plane; (b) XZ plane; and (c) YZ plane.

In Figure 4.27 and in the table 4.3 the comportment of the both is compared, although the gain looks better to $h_2 = 25.6\text{mm}$ it is not a real value if the radiation patterns will be compared. Since

that in the majority the curve that trace the limits of an IFA new model are better than the other. In this way, the selected topology have the dimensions presents in the table 4.4.

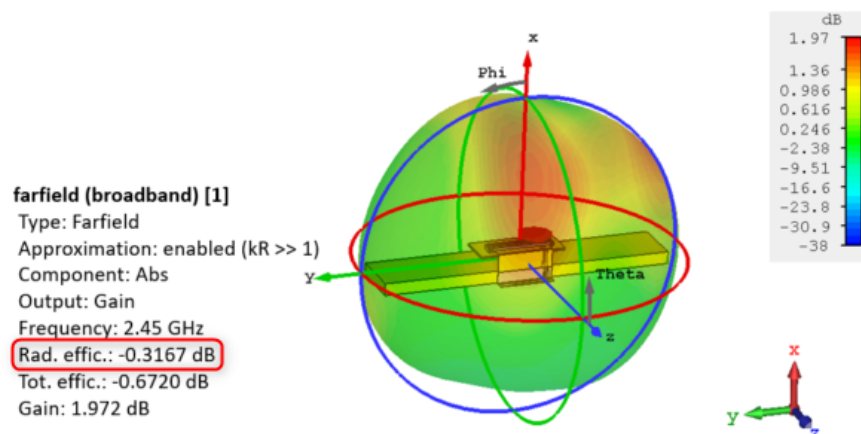


Figure 4.28: Simulated 3D radiation pattern comparison between the both antennas with display.

	t	h_1	h_2	g	s	f
Dimensions (mm)	1	10	20.5	1.05	1.05	0.22

Table 4.4: Final IFA dimensions with refer of 3.3.

Due the time constraints, the parametric antenna tuning had few interactions and the chosen antenna represents the best compromise between the impedance and the remaining characteristics.

4.5.2 Base PCB and Antenna Flexible PCB Layouts

To finish prototyping, the layout of the antenna flexible PCB and the base PCB with connector has to be sized. KiCAD software was used for this purpose and all the dimensions used were those of the last simulated model. Refer to table 4.4 on the flexible antenna layout, the footprint for a coaxial connector was inserted, with a resistor bridge, to measure the connector response (S_{21}), with this same PCB.

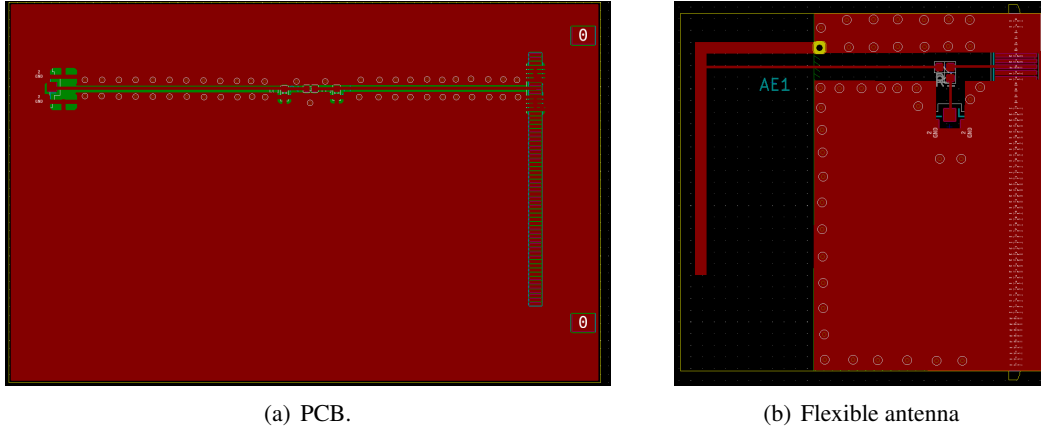


Figure 4.29: Layout implementation.

4.6 Summary

During this Chapter, important choices were taken. Firstly, in relation to the proposed solution, in section 4.1, were the flexible antenna through the FPC/FFC connector. Then, the connector response was analysed and validated, in section 4.2 and in section 4.3 the antenna on flexible through the connector was confirmed. The integration of the flexible antenna on the cluster was implemented and the antenna parameters have remain suitable, in section 4.4. Finally, in section 4.5 the prototyping was done.

Chapter 5

Antenna characterisation and results

In section 5.1 the connector measured prototype characteristics are discussed and evaluated and the test setup described. Then, in section 5.2, the same is done with the flat antenna on flexible substrate. In the last section 5.3, the final solutions are detailed described and evaluated as well.

5.1 Connector

After production, the arrived components were the ones in the figure 5.1. In figure is shown the previously dimensioned PCBs, described in chapter 4, as well as the FPC/FFC connector. In order to test the response of the connector could offer, the S-parameters were measured with the Vector Network Analyzer (VNA) (RD ZVL6). Port 1 was inserted on the antenna PCB while Port 2 is connected to the connector PCB. Figure 5.2 depicts these results, in a range starting from 0.5 GHz and ending at 3.5 GHz.

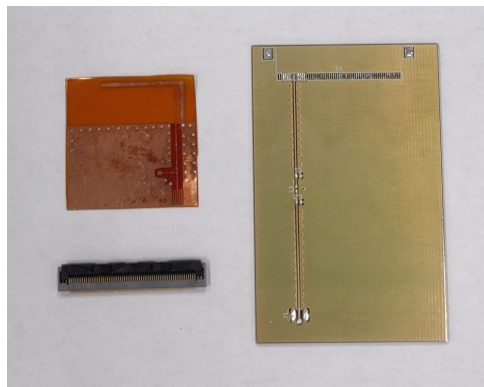


Figure 5.1: Prototypes of the flexible antenna, connector PCB and FPC/FFC connector.

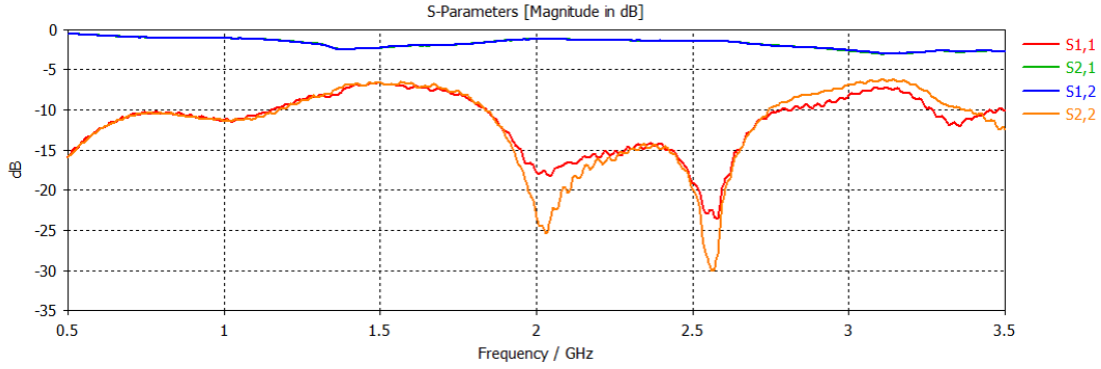


Figure 5.2: Measured S-Parameters of the connector PCB to the antenna PCB, through FPC/FFC connector.

When compared to simulated results in figure 4.3, some differences, degradation of performance is clear. This can be explained due to losses on port connections (UFL connectors) and on the transmission lines, plus lumped element components (0Ω). However, on the band of interest the FPC/FFC connector sports a reflection coefficient below -10dB and an insertion loss above -3dB which turns this transmission viable, between 1.8GHz and 2.7GHz . The S_{11} value at 2.45GHz is -15.7dB and S_{12} is around -1.4dB , which are in accordance with the simulated.

5.2 Flat Antenna

In practice, since there is a coaxial cable extension on the PCB up to the calibrated port and then a transmission line to the actual load, there's some phase difference in smith chart measurement, as well as some amplitude shift due to losses.

To eliminate this delay, a deembedding (also called port extension) procedure was done. Firstly, without any flexible PCB on the connector and using a feature of the VNA that can measure the distance from the port to the location on PCB where an open or short circuit appear. This measurement is made with the help of the Smith Chart where the open circuit is easy to identify, which corresponds to the resistive axis on the right side of the chart [26]. Then, the length is determined and the delay can be removed from the measurement.

In Figure 5.3 the simulation and the experimental results are compared.

As can be observed in the figure 5.3, the experimental and simulated antenna have a very similar response. As discussed in section 2.1.10, the impedance matching was done with a L-network. For the prototype antenna the same approach was carried out, having an initial impedance of $48.65 - j41.17\Omega$. Therefore, an inductor was included in series to move the load in the constant resistance circle, until the impedance $21.9 + j26.1\Omega$, with a value of 2.2nH . Then, a capacitor of 1.4pF was used to move close to 50Ω the responsible for this step.

The return loss response after the matching can be seen in Figure 5.4. According to it, it is clear this antenna can operate at the desired frequencies band.

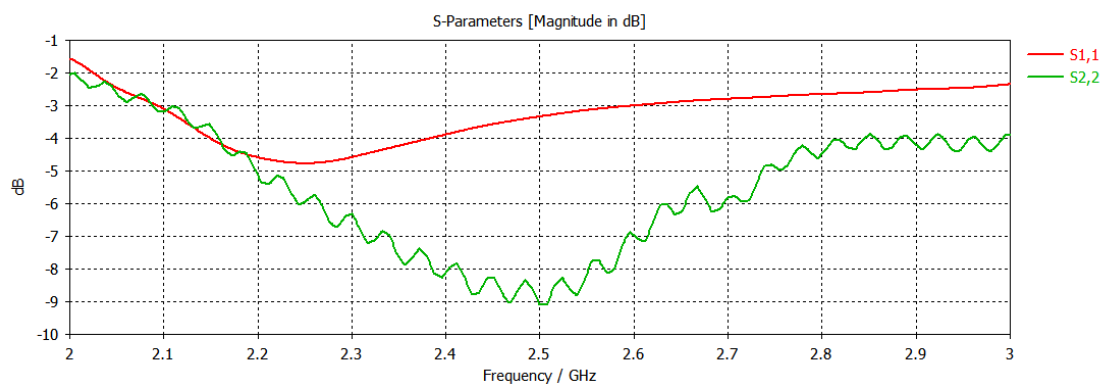


Figure 5.3: Simulated versus measurements of the return loss from the flat antenna through the connector and the PCB.

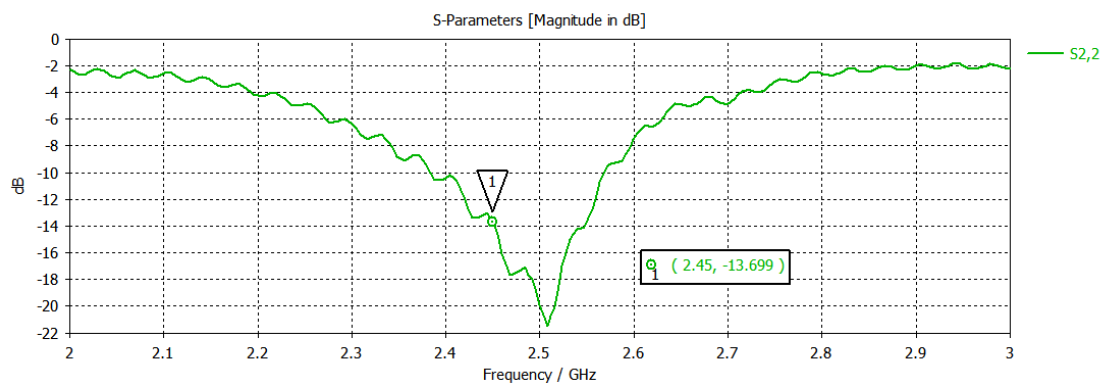


Figure 5.4: Measured return loss of flat antenna with a matching network.

After the correct tuning of the antenna, the radiation pattern was measured inside an anechoic chamber. For that a reference horn antenna (LB-20180-SF) was used, with which the estimated gain was calculated by direct comparison.

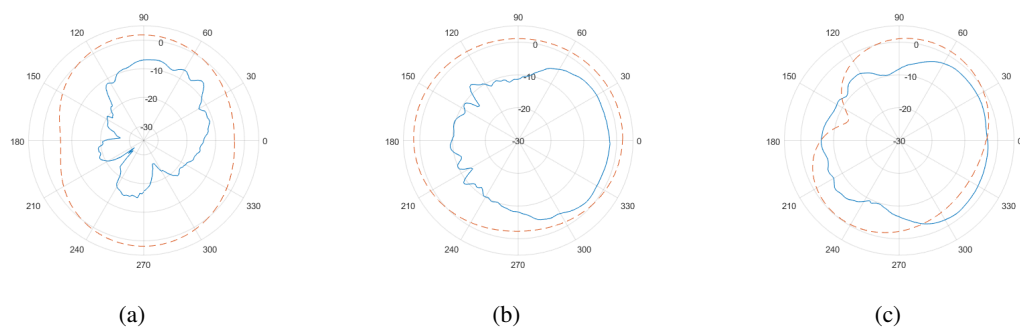


Figure 5.5: Measured(blue) versus simulated (red) 2D radiation pattern of the flat match antenna at: (a) XY plane; (b) XZ plane; and (c) YZ plane.

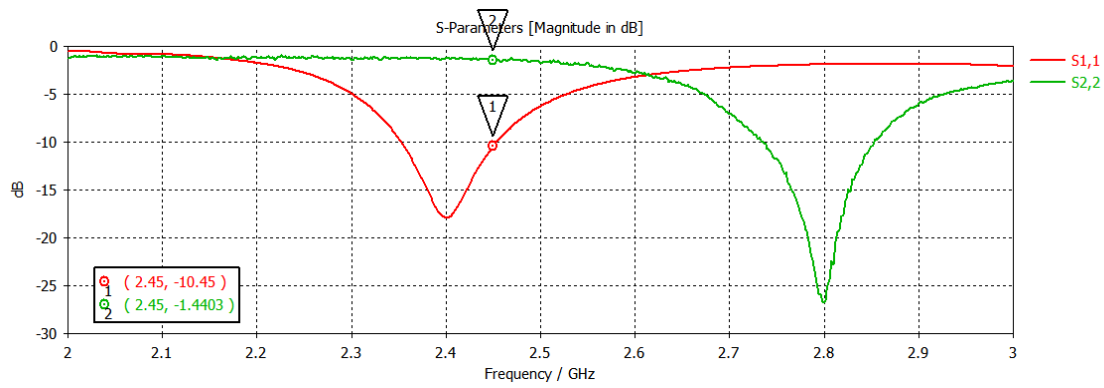


Figure 5.6: Simulated (red) versus measured (green) return loss of folded antenna inside of the instrument cluster.

As observed in the figure 5.5 and doing the correlation to the figure 4.12, it is clear that the antenna maintained the radiation characteristics. However, the gain has decreased from 1.894dBi to -0.4dB , between simulation and measurement.

5.3 Folded Antenna

After the flat antenna analysis, it is necessary characterise the folded response inside of the instrument cluster. Due to the main feature of the antenna being the flexibility, it is necessary take in mind, that the antenna response can change drastically in function of the antenna shape.

As observed in Figure 5.6, the measured result has a good return loss, however, it shows a different frequency than the one required. This is an unstable setup, due to the fabricated antenna having a different finishing from the typical flexible circuit PCB and does not offer sufficient stability. Hence, the matching using an impedance matching network is difficult to perform. Therefore, the radiation patterns of the folded antenna were measured without further matching and obtained at 2.8 GHz.

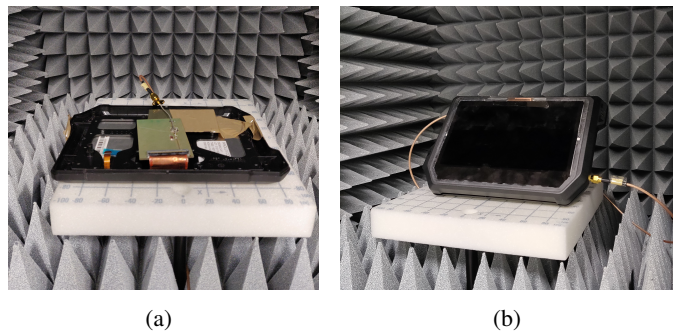


Figure 5.7: Folded antenna implemented on cluster instrumentation: (a) back view and ; (b) front view;

As observed in the radiation pattern of Figure 5.8, although the behaviour of the antenna is similar to the simulated refer to Figure 4.27, the gain stays below expectations, with a measured gain of 1.97dBi compared to -6dBi : from simulation.

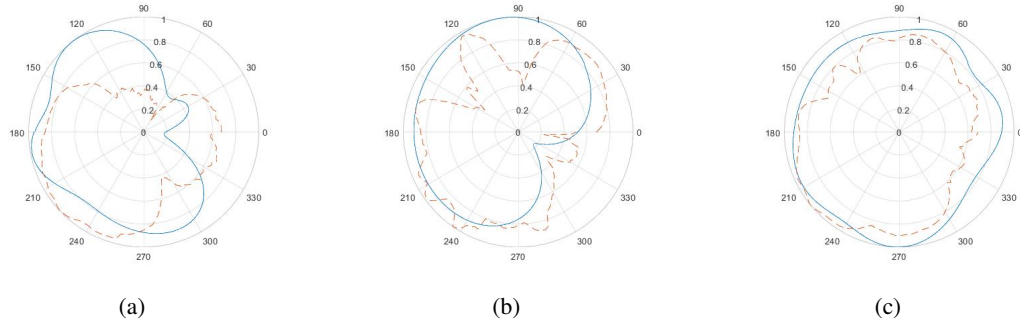


Figure 5.8: Normalized measured (red) versus normalized simulated (blue) 2D radiation pattern of the folded antenna inside the instrumentation cluster: (a) XY plane; (b) XZ plane; and (c) YZ plane.

With the results shown in Figure 5.6 and in 5.8, it is clear that some notary differences occur relatively to the simulation. These can be result of several points. Such as the UFL connectors that are fragile and a source of losses which were no simulated, the FPC/FFC connector after some interaction loss capacity of ensuring the transmission. As well as, the used simulation model that were simple in comparison with the measured. The shape as the antenna is folded influence how the antenna characteristics since that is a manual and mechanical process. Finally, as the antenna PCB is close to the housing cluster (PBT-ASA-GF30) that have a higher dissipation factor.

5.4 Summary

As conclusion, in this Chapter, the measured results were analysed and compared with simulation. In section 5.1, the FPC/FFC connector response is analysed and validated. Also the same procedure was presented for the flat antenna with a response close to the simulated in section 5.2. Finally, the folded, in section 5.3 have been measured and compared.

Chapter 6

Conclusions and Future Work

In section 6.1 the work will be reviewed and the comparison with the initial goals will be performed. Then, the future work of this project will be discussed, in the section 6.2.

6.1 Conclusions and Remark

In the first part of this thesis, on Chapter 2, the state of the art related to antenna theory was made. In the same chapter an expanded analysis of the environment possibilities having in mind this specific application.

In Chapter 3 we described some considerations of the IFA in order to better understand how to implement the desired typology.

Further, in Chapter 4, all the antenna design and respective simulation were presented. Firstly, a comparison between all the possible typologies was made, being the antenna on flexible substrate the chosen one, since this implementation solve limitations of connection, space and cost.

Then, in Chapter 5, the characterisation of the antenna and the comparison with the simulated results were performed.

At the beginning and as observed from simulation, it seems clear that a flexible board could be implemented as an antenna and that the FPC/FFC could work as a connector between the flex and the rigid PCB with the main circuit, at the RF frequencies of interest without need for components on the flex side. Besides that, the results of the simulated antennas had the expected performance, and all the requirements were fulfilled. The radiation pattern was omnidirectional having a doughnut shape. The bandwidth of the antenna covers the entire frequency range of interest, with a good return loss after matching with an L matching network. The simulated efficiency was above 90% which represents a considerable improvement to the chip antennas. The antenna occupies a portion of the cluster that is not populated at the time and does not bring extra constraints to the remaining elements. Concerning cost of material and manufacturing assembling constraints (available space inside the cluster housing), this was considered an improvement, recording the extra cost is null given this antenna is being integrated in an existing flexible board. The time and effort in the production line is the same, since no extra step has to be introduced.

After prototyping, the characterisation of the connector response was not so good as predicted by simulation. Nevertheless, the measured results have shown that the FPC/FFC connection performance well for the transmission of signals at 2.45 GHz.

The flat antenna results match to simulations, where the bandwidth was respected and the gain in certain directions was approximate. However, when the flexible antenna is folded, the antenna response changes and the frequency bandwidth suffers a shift in comparison with the simulation. During the experimental analysis, it was verified that any change in the position of the setup results in a change of the S-parameters values and as a consequence in all the parameters of the antenna.

The prototype solution has presented some constraints, relatively to finishing of the PCBs, shape of the antenna and connectors response.

6.2 Future Work

Due to time constraints further improvements were not possible to implement. These are discussed in this section. Firstly, the connector response, that can be improved with a better substrate for the PCB, which is a source of high losses. During the experiment it was realised that the connector loses compression strength with the number of utilisations. This is a problem, from the examination point of view, although not a problem for the product itself, since this connector will be open and closed only once in its lifetime, or half a dozen times in the worst case scenario.

Another proposed improvement could be the solder mask that the flexible board is missing above the copper, which is exposed to oxidation, that can lead to degradation of performance. This can be prevented if a new prototype is built with a mass production finishing. That mass production would also allow the flexible PCB to correct pre-bend at the connect position, making its behaviour more stable.

The final step would be to design the antenna alongside the signal tracks of the display flexible PCB and have the solution completely integrated.

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