INSTITUTO SUPERIOR DE ENGENHARIA DE LISBOA

Departamento de Engenharia de Eletrónica e Telecomunicações e de Computadores

ISEL

Reconfigurable Antenna for Mobile Terminal

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Abstract

Reconfigurable antennas are capable of actively changing their radiation properties, such as resonant frequency, radiation pattern and/or polarization. These bring a lot of versatility to current wireless communication electronic design, since one can use a single antenna to cover different services, instead of using multiple antennas.

The use of reconfigurable antennas helps overcoming incapacities of conventional antennas and improving the system recital, for instance, it can be seen in applications like cognitive radio where system parameters vary with the circumstances and the antenna needs to be adaptable to these changes.

This dissertation discusses some components that can be used in an antenna to enable reconfigurability, such as PIN Diodes (Positive-Intrinsic-Negative) or MOSFET 's (Metal Oxide Semiconductor-Field Effect Transistors). Printed monopole antennas are designed, with which these two components are coupled in order to evaluate the feasibility and advantages/disadvantages of each of these switch components.

Keywords: Antenna; Reconfigurable Antennas; PIN Diodes; MOSFET 's; Frequency; Polarization, Radiation Pattern.

Resumo

Antenas reconfiguráveis são capazes de mudar ativamente as suas caracteristicas de radiação, tais como a, frequência de ressonância, diagrama de radiação ou de polarização.

Este tipo de antenas trazem muita versatilidade aos actuais sistemas de telecomunicações, dado que, pode utilizar uma única antena para cobrir diferentes bandas de frequência, em vez de utilizar várias antenas.

O uso de antenas reconfiguráveis ajudam a superar algumas das incapacidades das antenas convencionais. Superação em termos de melhoria do sistema, considerando, por exemplo, que o sistema, pode ser visto em aplicações como o rádio cognitivo (sistema rádio inteligente que pode ser programado e configurado dinamicamente) onde os parâmetros do sistema variam de acordo com as circunstâncias e onde a antena necessita de ser adaptável a essas mudanças.

Esta dissertação discute alguns componentes que podem ser utilizadas numa antena reconfigurável, de modo a permitir a sua reconfiguração. Componentes como: Díodos PIN (*Positive - Intrinsic - Negative*) ou MOSFET 's (*Metal Oxide Semiconductor-Field Effect Transistors*), onde antenas impressas são desenhadas e estudadas, com a presença destes dois componentes, os quais estão acoplados, de modo a avaliar a viabilidade, vantagens e desvantagens de cada um destes componentes de comutação.

Palavras-chave: Antenas; Antenas Reconfiguráveis; Díodos PIN; MOSFET 's; Frequência; Polarização, Padrão de Radiação.

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Acronyms

ADEETC Àrea Departamental de Engenharia de Eletrónica e Telecomunicações e de Computadores

CST Computer Simulation Technology

CPW Coplanar Waveguide

DNG Double-negative

FET Field Effect Transistor

GSM Global System for Mobile Communications

HPBW Half-Power Beam Width

ISEL Instituto Superior de Engenharia de Lisboa

IEEE Institute of Electrical and Electronics Engineers

MOSFET Metal Oxide Semiconductor-Field Effect Transistor

PCB Printed Circuits Board

PIFA Planar inverted F antenna

PIN Positive - Intrinsic - Negative

RECAP Reconfigurable Aperture

RF Radio Frequency

RF-MEMS Radio-Frequency Microelectromechanical Systems

RL Return Loss

UMTS Universal Mobile Telecomunications System

USB Universal Serial Bus

UWB Ultra Wide Band

WLAN Wireless Local Area Network

Chapter 1

1.1 Introduction

With the increasing number of technologies related to communication devices, the need for multifunction systems is growing and this makes antenna study and the search for new structures capable of responding to multiple frequencies a requirement.

More recently, there has been a focus on the research of Ultra Wide Band (UWB) antennas, which are broadband antennas, in the order of several GHz. In addition to the multi-band antennas or very large band antennas there is the concept of reconfigurable antennas, that has also been the subject of much attention by researchers.

Reconfigurable antennas are required to comply with various wireless services that are distributed over a considerable frequency range. The configurability is achieved in most cases by switches, and multiple antennas can have different behavior when changing the state of such switches. One can change the operating frequency, the radiation pattern and polarization in accordance to the purpose of each antenna. These types will be studied in the next section.

1.2 Objectives

This dissertation aims to present a possible solution for the implementation of a frequency reconfigurable antenna frequency to operate in Universal Mobile Telecommunication System (UMTS) and Wireless Local Area Network (WLAN) bands. To obtain the reconfigurability, PIN diodes are used to implement switches. The small size of the antenna alongside with the versatility of frequency diversity makes this a very interesting solution to apply in sensors or SDR systems (Software Defined Radio) with cognitive capacity of the environment radio.

For studies and simulations of antennas, we used the simulation software *Computer Simulation Technology (CST) Microwave Studio 2014®* [1] and a comprehensive review is required for acquiring knowledge about the antenna design. The main parameters that characterize the functioning of an antenna, will be follow and the design parameters of the project will be optimized to achieve the best results. The measurement results will be in terms of return loss and radiation pattern in different modes.

1.3 Dissertation Structure

This thesis consists of four chapters. The chapters are inter-dependent and the reader should follow the presented order to better understand the contributions presented in the thesis.

After the introduction, motivation and objectives in Chapter 1, Chapter 2 of this dissertation gives a brief introduction about compact antennas for mobile terminals, referring some recent developments in this area and addressing some techniques used in miniaturization. In addition, Chapter 2 will focus on the investigation technology the reconfigurable antenna, in order to tackle the antenna size issues to satisfy multi-mode, multi-band and multi-function requirements. In Chapter 3, five structures used as a reference to the antenna will be studied and simulated. A Reference Structure of a Printed Monopole, one with 'L' shape, other with 'C' shape and they are used for comparison purposes. In same Chapter, the details of how they function are described in the final reconfigurable antenna with Diode PIN and the one with MOSFET are presented respectively, as well as all the steps and decisions taken. It also presents the results obtained in simulations. The main conclusions and possible future work are discussed in Chapter 4.

Chapter 2

2 Antennas for Mobile Terminals and Reconfigurability

2.1 Introduction

Portable communication devices such as mobile phones and laptops are currently part of the daily lives of most people. Therefore, it is desirable such devices have the smallest possible volume, are light and that their cost must be reduced. However, this drastic reduction in the devices size has undermined the antenna's issue as they integrate one of the device's larger components but the evolution of electronics in recent decades has been able to satisfy these requirements. Thus, much effort has been directed to the miniaturization of the antennas' size in order to meet the demand for smaller size and volume devices.

To meet this demand, much attention has been given to compact printed antennas. Printed compact antennas are antennas with a narrow band and a wide beam, manufactured attaching the antenna metallic pattern on a dielectric substrate having a metal layer on the face opposite to the substrate serving as a ground plane [2]. This type of antenna has very attractive characteristics, specially its profile and reduced weight. It is also easily integrated into Printed Circuits Board (PCB). Due to the manufacturing process for printed circuits, its cost is low, the substrate being the most expensive part of the circuit. It is noted that the compact printed antennas present a great versatility in terms of impedance, operating frequency, radiation pattern, polarization mode and through changes in the shape of the antenna and feeding method [3]. The fact that such antennas are easily designed to operate with horizontal or vertical polarization, through the use of multiple feed points or an asymmetrical feed network, allows it to be used in various communication systems.

Microstrip antenna is characterized by having an inherent narrow bandwidth and in the last decade, studies have been published with significant advances in relation to bandwidth, which allowed using these antennas in several applications. Section 2.2 addresses several publications on this type of antennas.

This chapter will address some of the advances in compact printed antennas, being given greater relevance to microstrip antennas, as well as possible applications in many broadband systems (UWB). Some miniaturization techniques are also mentioned.

2.2 State of the Art in Microstrip Antennas

In recent years, there has been a significant progress in the design of microstrip antennas with broadband, multiple resonance frequencies and dual polarization. To obtain a printed microstrip antenna with reduced dimensions at a specific frequency of operation, the usage of a substrate with high permittivity is an effective method. It has also been shown that placing a shorting pin, as seen in Figure 1 and 2 can effectively reduce the antenna size for a given frequency. The use of the meander antenna patch, combined with the primary technique has also been successfully used [4] [5] [6].

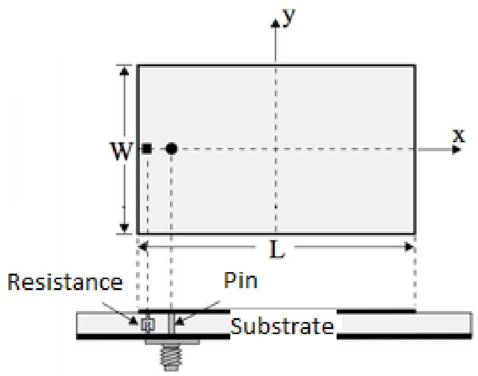

Figure 1: Geometry of a rectangular compact antenna microstrip with short circuit pin [2]

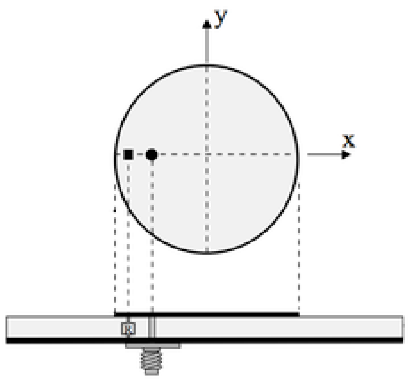

Figure 2: Geometry of a circular compact antenna microstrip with short circuit pin [2]

Applying the technical bend of the ground plane of a microstrip antenna we can get a significant lowering of the fundamental resonance frequency similar to that obtained when using the meander antenna [7]. It is also possible to increase the impedance bandwidth and the antenna gain, which is an advantage of the bend method of the ground plane in relation to the patch antenna.

Another type of compact printed antenna is the planar inverted F antenna (PIFA), which derives from a printed antenna of a quarter wavelengths. An example of a PIFA antenna can be seen in Figure 3.

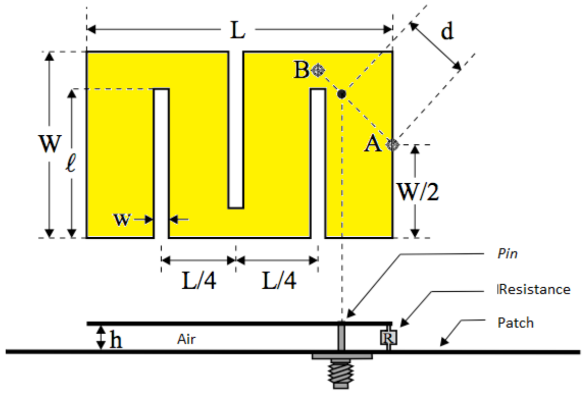

Figure 3: Example of a PIFA antenna with bend of the patch [8]

A PIFA antenna is an antenna that is obtained by a short-circuit between the radiating element or patch and the ground plane through a short circuit Pin. Thus, the antenna resonates at a lower frequency while retaining a small size. The fact that the PIFA antenna having a reduced size. It made them very attractive for applications in mobile phones with indoor antenna, creating use of a transparent template for the user, where it is unaware of its presence. They also have the advantage of its radiation pattern being such that its emission in the user's head direction is smaller [9].

In [10] and [11] a compact design is discussed for using an inverted L-shaped planar patch (PIL) that functions as an antenna of a quarter wavelengths, but with a radiation pattern similar to a microstrip antenna of half wavelength. The size of the antenna can be reduced to a fixed frequency of operation using a printed antenna PIL instead of the conventional microstrip antenna. The use of a metallization in the form of inverted U is also a way to obtain a compact microstrip antenna. The surface current flowing through the metallization of the antenna can be effectively extended and thus the fundamental resonance frequency of the antenna can be reduced significantly [12]. This behavior allows you to find antennas with a large size reduction to a fixed operating frequency [2].

There is also interest in reconfigurable printed microstrip antennas. In [13], a printed antenna using a reconfigurable optical switch to operate at three different frequencies: 4.55 GHz, 4.78 GHz and 5.10 GHz are present. This approach has the advantage of eliminating the need to use electrical controllers, reducing concerns about the electromagnetic compatibility with particular interest in its use in sub-millimeter regime, which inhibits the physical dimensions of electrical controllers. The optical switches used in [13] are silicon pieces with high resistivity, of which conductivity increases in the presence of infrared light.

The technology based on the ultra-wide band system (UWB) has recently attracted attention, because to lower the limit indexes of emissions has been regarded as a model for short wireless communication system range and high output, including Wireless USB systems [14]. One of the challenges in UWB systems is the antenna's design which to cover the system should operate in a frequency band between 3.1 and 10.6 GHz and at the same time maintain reduced size to apply in portable devices. In [15] a slot antenna for a frequency band between 2.3 and 10.9 GHz is proposed. The addition of two notches with an open slot in the ground plane has improved the functioning of the antenna in the bandwidth from 2.3 to 10.9 GHz.

Interest in Wireless Universal Serial Bus (USB) [16] technology, which promises to bring high-speed secure connections within walking distance using a sub-band UWB, increased the need for small size antennas with this band coverage. In [17] techniques used in the reduction of high-performance UWB antenna size are reported. It has been shown that the performance of the antenna has ground plane dependence and that at the cut of the antenna where current distribution is weak; we can obtain a reduced antenna size without damage its operation. The antenna before size reduction can be seen in Figure 4 and after size reduction in Figure 5.

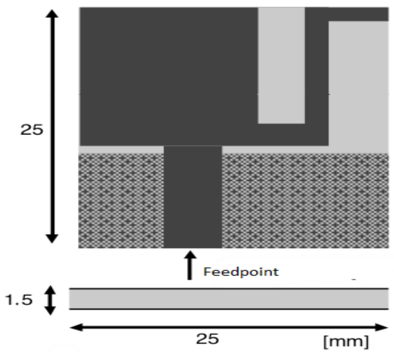

Figure 4: UWB antenna with ground plane size [17]

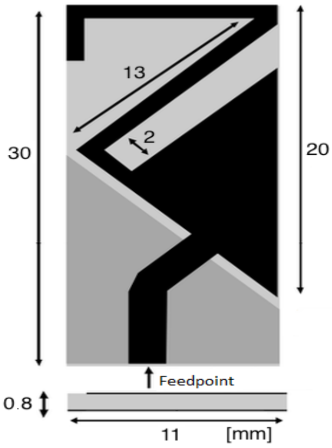

Figure 5: UWB antenna with reduced size. Final Structure [17]

In [18] a flexible antenna is proposed for operation at 2.4 and 5 GHz. Builted with a flexible printed circuit made in copper film base, coupled to a permittivity of 3.3 polyamide film with the thicknesses of the two films with 12 and 25 microns respectively. This antenna is represented in Figure 6. The antenna maintains two operating bands, even when bent, showing it to be suitable for its use in mobile terminals.

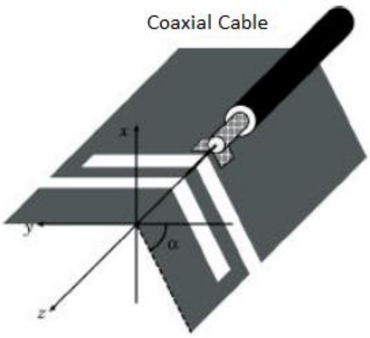

Figure 6: Flexible antenna for WLAN applications [18]

Recently the use of metamaterials has been considered as substrates for printed antennas. Metamaterials are artificially created structures, which have unique properties not existing in nature. There are several kinds of metamaterials, such as double negative (DNG), having a negative effective permeability and a permittivity wave propagation resulting in a polarization remaining a negative refractive index. The electromagnetic structures 'band-gap' (EBG) allows to prevent the propagation of electromagnetic waves at a certain frequency for certain angles and input polarizations. Finally, there are ground planes that have unique reflective characteristics, different from conventional PEC, called artificial complex ground plans [19].

In [20] metamaterials are used in the substrate of a printed microstrip antenna with the aim of achieving an operating frequency of 76 GHz and 81 GHz for radar application. It has been shown that it is possible to enhance the electromagnetic wave propagated along the patch, significantly extending the operating bandwidth, using a substrate with a pattern of planar metamaterial a printed microstrip antenna, also reaching an improvement of efficiency and reduce losses [21].

2.3 Techniques of Miniaturization

In recent decades, large reductions were achieved concerning the round size for implementation in mobile terminals. Today most of these terminals have indoor antennas that go unnoticed to the user. However, these continue to be the component that most limits the miniaturization of terminals. In general, small sized antennas in mobile terminals are either electrical, physical, or functional, or even considering when the antenna is not electrically or physically small, as long as it has a number of additional physical dimensions without increasing functions. This means that the miniaturization of antennas for mobile terminals can be made in several ways depending on the application has in mind. The design and optimization of antenna geometry, in particular the shape and orientation of the patch and the mesh and feeding, constitutes a common approach in the design of antennas. The use of non-conductive material such as ferrite or high permittivity dielectric material and the application of special manufacturing processes are also methods used to achieve small size antenna [22].

In the case of printed microstrip antenna, several techniques have been reported to reduce their size to a particular operating frequency. The microstrip antennas are usually half-wavelength structures operating in TM_{01} or TM_{10} mode with a resonance frequency in the case of a rectangular antenna with a thin substrate is given by:

$$f \cong \frac{c}{2\, l \sqrt{\varepsilon_R}} \tag{2.1}$$

where ‘c’ is the speed of light, ‘l’ is the length of the patch antenna and ‘ε_R’ is the relative permittivity of the substrate. From equation 2.1 it can be concluded that the microstrip patch antenna has a resonant length directly proportional to $\frac{1}{\sqrt{\varepsilon r}}$. Furthermore, using a substrate with higher permittivity can result in a smaller physical size of antenna for a given frequency.

The use of a short-circuit between the end of the patch antenna and the ground plane is a known method for reducing dimensions, making it function as an antenna structure of a fourth wavelength. When a pin is used in the short circuit the frequency operation can be reduced, allowing further reductions in the antenna size, so this allows reducing the antenna length by half at a given operating frequency.

The use of the meandered patch to increase the flow path surface is also an effective method to reduce the operating frequency of the antenna. In the case of a rectangular patch, the meander can be obtained by cuts made in the non-radiating edges. In Figure 7, it is shown that the surface currents run through the meander, so there is becomes the largest path and consequently the working frequency is reduced.

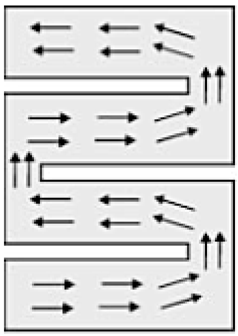

Figure 7: Distribution of surface current in a meandered patch [2]

There are also other types of cuts, as in Figure 8, introducing new resonant frequencies and different polarization [2].

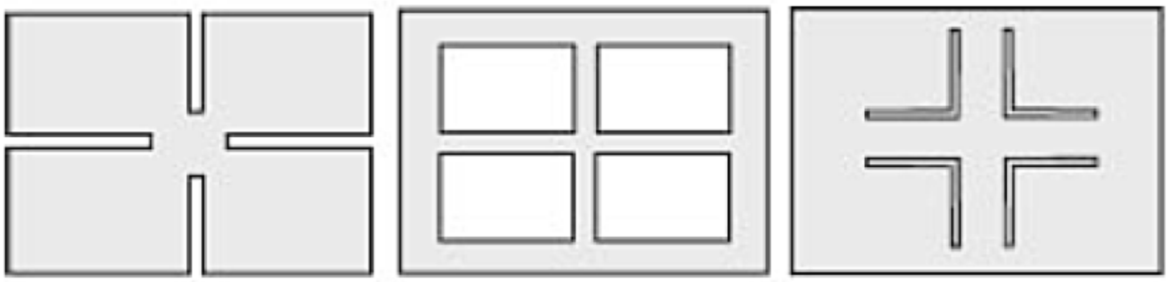

Figure 8: Examples of cuts in patch antenna [2]

2.4 Reconfigurable Antennas

2.4.1 Techniques used in Reconfigurable Antenna

Currently there are six main types of reconfigurable techniques, which are used to implement reconfigurable antennas, as shown in Figure 9.

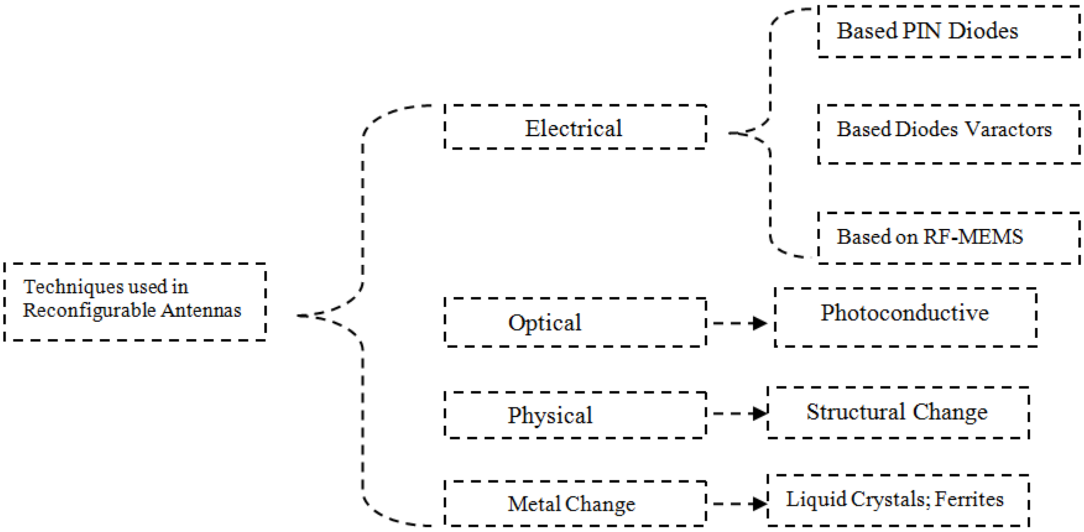

Figure 9: Techniques used in Reconfigurable Antennas

An electrically reconfigurable antenna relies on electronic switching components (RF-MEMS, PIN Diodes, or varactors) to redistribute the surface currents, and alter the antenna radiating structure topology and/or radiating edges. The integration of switches into the antenna structure makes it easier for designers to reach the desired reconfigurable functionality.

The easy integration of such switching elements into the antenna structure has attracted antenna researchers to this type of reconfigurable antennas despite the numerous issues surrounding such reconfiguration techniques. These issues include the nonlinearity effects of switches, and the interference, losses, and negative effect of the biasing lines used to control the state of the switching components on the antenna radiation pattern. Next, three different examples of electrically reconfigurable antennas are described. Each example discusses the use of a different reconfiguration technique to reach the corresponding function.

I. Based on PIN Diodes

A PIN diode is a semiconductor device that operates as a variable resistor at microwave frequencies. PIN diodes are popular in microwave circuit applications because of their fast switching times and high capacity, sometimes they are used as input protection devices for high frequency test probes. If the input signal is within range, the PIN diode has little impact as a small capacitance. If the signal is large, then the PIN diode starts to conduct and becomes a resistor that shunts most of the signal to ground [23]. The construction of a PIN diode is illustrated in Figure 10.

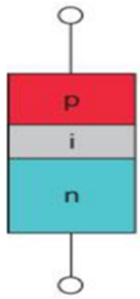

Figure 10: Pin Diode

The 'P' and 'N' types are separated by an intrinsic region 'I'. 'P' contact is the anode and 'N' is the cathode contact. This is shown in Figure 11, where the anode is the arrow and the cathode is the vertical bar. The region between 'P' and 'N' is the Intrinsic. The width of this region has an important role in the performance of the PIN diode, being the advantage the better long wavelength response of the former. In case of long wavelength irradiation, photons penetrate deep into the cell. Only those electron-hole pairs generated in and near the depletion region contribute to current generation. The depletion region of a PIN structure extends across the intrinsic region, deep into the device. This wider depletion width enables electron-hole pair generation deep within the device. This increases the quantum efficiency of the cell [23].

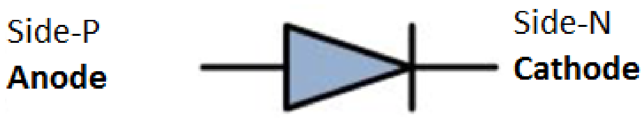

Figure 11: Structure of Pin Diode

The Figure 12 shows a simple equivalent circuit of a Pin Diode at Radio Frequency (RF) regime. In forward bias, the PIN diode has an equivalent circuit corresponding to an inductor in series with a resistor. While in reverse, bias results are equivalent to an inductor in series with a parallel resistor and a capacitor.

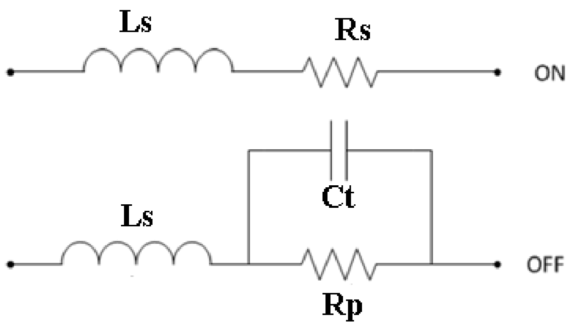

Figure 12: Equivalent Circuit of Pin Diode

An example of a reconfigurable antenna based on PIN diodes is shown in Figure 13 (a), is a patch antenna, so therefore has one layer and below is all ground plane individually controllable switches achieve changes in the configuration, each are implemented as one or more PIN diodes. A developed prototype antenna is shown in Figure 13 (b). According to the different combinations of the diodes: ‘ON’ or ‘OFF’ that is how it will be operated in the standard frequency/antenna radiation. The proposed antenna operating in the UWB (3.1-10.6 GHz) range, where the Diodes, D1 and D2, states were: D1 ‘On’, D2 ‘On’; D1 ‘off’; D2 ‘on’; D1 ‘On’, D2 ‘Off’; D1 ‘Off’, D2 ‘Off’, Consider state 1 to state 4 the antenna is tuned to single band and dual band modes. Therefore, the designed antenna will not operate efficiently in this frequency range. The resulting antenna operates in different narrow band and dual band modes with acceptable gain and return loss. With the elimination of the particular band the data transmission rate increases also unwanted delay for transmission reduces.

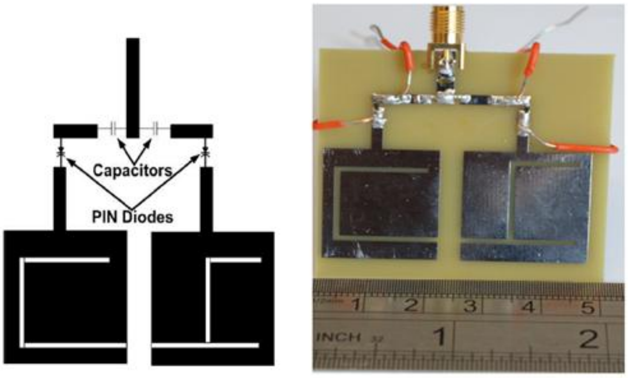

Figure 13: Reconfigurable antenna with PIN Diode (a); Prototype (b) [24]

II. Based on Varactor Diodes

The varactor diode is a semiconductor diode with a small junction capacitance, which varies with the voltage applied in the bias. They are an important component in RF applications. Varactor diodes are widely used in communication applications when it is necessary to carry out any relaying. Consisting of a P-N junction diode. The circuit symbol for a varactor diode is shown in Figure 14.

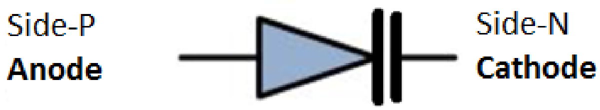

Figure 14: Structure of a Varactor Diode

The electrical capacity of a varactor decreases when the voltage becomes larger and the varactor tuning is represented according to the equivalent circuit shown in Figure 15 [25].

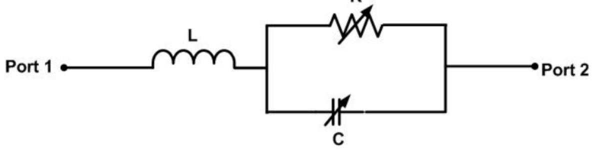

Figure 15: Equivalent circuit Diode Varactor

Single and dual-polarized slot-ring antennas with wideband tuning using varactor diodes have been demonstrated in [26]. The single-polarized antenna tunes from 0.95 to 1.8 GHz have better than 13-dB return loss. Both polarizations of the dual-polarized antenna tune from 0.93 to 1.6 GHz, independently, have better than 10-dB return loss and greater than 20-dB port-to-port isolation over most of the tuning range. The capacitance of the varactor diodes varies from 0.45 to 2.5 pF. The dual-polarized slot-ring antenna can either be made for both frequency and polarization agile simultaneously, or can operate at two independent frequencies on two orthogonal polarizations. The corresponding antenna structure for single- and dual polarized slot-ring antennas is shown in Figure 16.

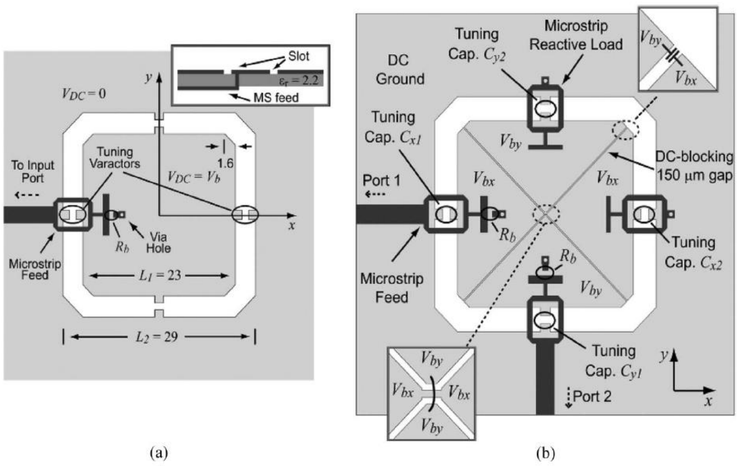

Figure 16: (a) Single-polarized slot-ring antenna. (b) Dual-polarized slot-ring antenna [26]

III. Based on RF-MEMS

Switches are devices that use mechanical movement to achieve a short circuit or an open circuit in the RF transmission line. The forces required for the mechanical movement can be obtained using models, electrostatic or magneto static heat.

Over the past decade, the RF MEMS switches have been used to be applied in telecommunications due to many advantages, instead of other options such as small in size, good linearity and good insulation. However, these require high DC voltage action [27]. MEMS switches are used in various applications such as phase shifter within the range of Giga Hertz (GHz), switching, reconfiguring networks and low power oscillators [28]-[29].

A cross section of a MEMS switch is shown in Figure 17 [30] and an example of MEMS in practice is shown in Figure 18 [31].

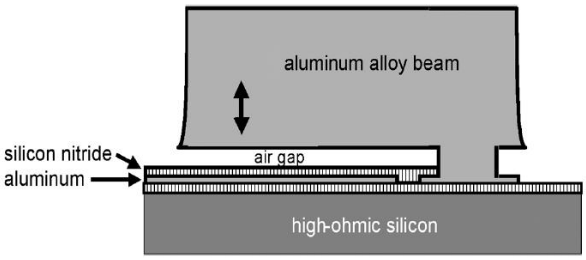

Figure 17: Cross section of a MEMS capacitive switch [30]

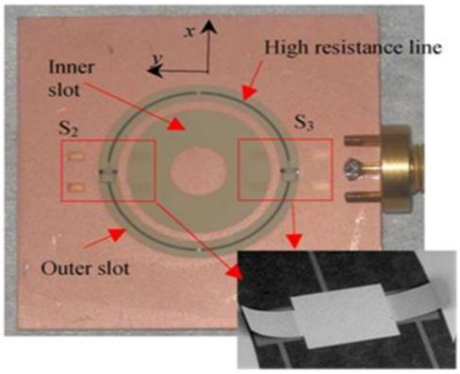

Figure 18: Integrated with two arms MEMS actuators [31]

2.4.2 Comparison between Different Techniques of Reconfiguration

The electronic switching components have been widely used to reconFigure antennas, especially after the onset of RF MEMS in 1998. One of the main advantages of such a component is its good insulation property providing low losses. Meanwhile is presented a novel RF MEMS switch mechanism in which the response is slower than the PIN diodes and has a response in a matter of nanoseconds. All these options, especially Varactors diodes, fit to add the scalability of reconfigurable antennas.

The easy integration into the antenna structure goes along its non-linearity effect (resistive and capacitive) and the need for high voltage (RF-MEMS; Varactor diodes). The activation of these switches requires lines of polarization that can adversely affect the radiation pattern of the antenna and add more losses. The incorporation of switches increases the complexity of the antenna structure due to the need for additional shunt capacitors and inductors.

Although optical switches are less popular, these are the ones with a most definitely reliable mechanism for reconfiguration especially when in comparison with RF MEMS. Moreover, these parameters are integrated into the antenna structure without complicating or biasing the lines, which eliminates unwanted interference losses and radiation pattern distortion. Despite all these advantages, optical switches exhibit lossy behavior and require a complex activation mechanism.

2.5 Types of Reconfigurable Antennas

The reconfigurability corresponding to each of the four categories can be obtained by a change in current distribution on the antenna surface, a change in power, or a change in the physical structure of the antenna. It is essential to note that changing a characteristic in the antenna structure or composition can affect the other parameters. Therefore, the implementation should be careful during the design process to assess all the characteristics of the antennas, and simultaneously, to achieve the reconfigurability. There are four ways to reconFigure the antennas as can be seen in Figure 19.

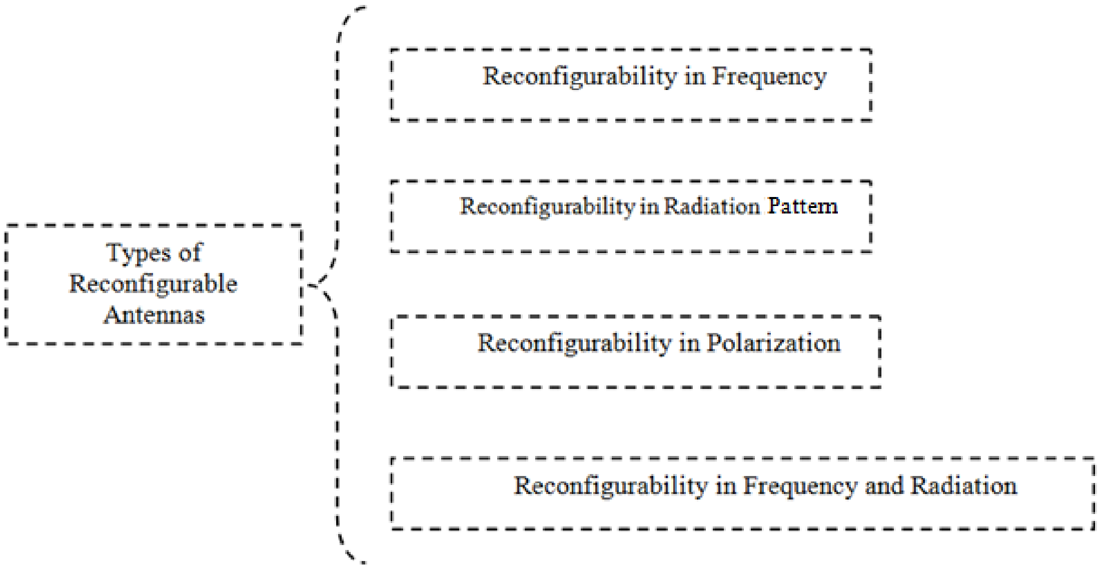

Figure 19: Types of Reconfigurable Antennas

2.5.1 Reconfigurability in Frequency

The first category is based on the frequency reconfigurability. The aim is to set/change the operating frequency of the antenna as a single multifunction antenna in a small terminal for diverse applications [32] - [33]. The shape of the radiation patterns of these antennas must remains unchanged while the frequencies are tuned/switched from one band to the other.

Reconfigurable antennas in frequency are classified into two categories:

1) **Switched:** This could be achieved through PIN diode switches (addressed in Section 2.4.1-I.), which are used in various instruments to operate in multiple bands. Examples include using a widely adjustable antenna PIN diodes [34], the change in the feed location to reconFigure the operating frequencies [35] and reconfigurable antenna [36] for satellite and terrestrial applications.

2) **Continuous:** This could be achieved through varactor diodes (discussed in section 2.4.2-II.). The antenna allows smooth transitions into or between operating bands without disturbances as in [37].

2.5.2 Reconfigurability in Radiation Pattern

The second category is based on the reconfiguration by default, where the frequency band remains unchanged, while radiation changes based on system requirements. The antenna can direct the main beam in different directions. This type of reconfigurability was recently studied in [38] using a Coplanar Waveguide (CPW) fed antenna. In [39], a reconfigurable antenna combining the frequency and including a radiation pattern reconfiguration.

2.5.3 Reconfigurability in Polarization

Polarization reconfigurability is appropriated to decrease the vulnerability to interfering signals contained in environments. It also provides an additional degree of freedom to achieve better link quality as a kind of antenna diversity switch [40]. The radiant structure that can change its polarization (horizontal/vertical, more or less than a 45° angle, circular polarization or left circular polarization to the right, etc.) is called polarization reconfigurable antenna. The antennas with polarization diversity orthogonal polarizations allow obtaining either linear or circular radiation.

2.5.3 Reconfigurability in Frequency and Radiation

This category is a combination of two of the above categories. For example, it is possible to achieve a frequency reconfigurable antenna with polarization diversity at the same time. In general, most of the antennas are capable of operating at any frequency or radiation pattern; however, the combination can be made with frequency and radiation patterns simultaneously. This is a phenomenon that occurs naturally and that is highly unattractive. The difficult in reconfigurable antennas is to change one of the characteristics and keep the remaining intact. It was proposed in [41] a frequency and radiation pattern of a microstrip antenna reconfigurable by multiple connections. Figure 20 illustrates the geometry of a switch placed in a patch antenna resonance frequency at 3.7 GHz with a polarized linear pattern.

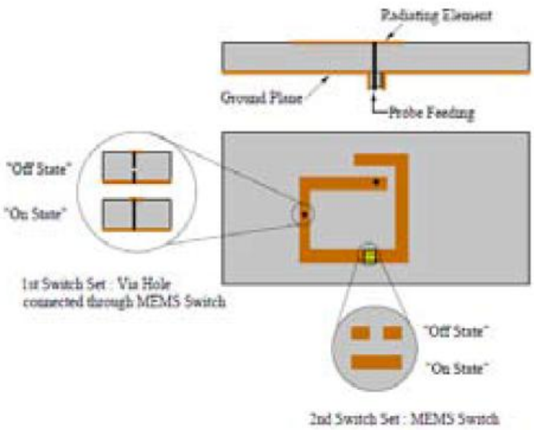

Figure 20: Geometry of a reconfigurable antenna capable of both reconfigurabilities [42]

Chapter 3

3. Project for a Printed Monopole Antenna with Reconfigurability

As stated before, this dissertation aims to project a compact antenna to be use in mobile terminals. This chapter will address three configurations which were the starting point for the final antenna, which is tuned to operate at standard frequency of 2.4 GHz, subjected to input S11 Parameters with reduced values throughout the whole bandwidth and it was built on one single conducting ‘l’ length upon a conducting plane, where $l=\frac{\lambda}{4}$. This way it was considered the empty wavelength of 125 mm. First is featured a Simple Printed Monopole in its operating bandwidth, as well as its radiation characteristics. After, some modifications into the structure in terms of size to maximize its operating band plus two other shapes of Printed Monopoles– designated as ‘L’ and ‘C’– where will be made changes into the structures in order to demonstrate and characterize their influence on the operating band antennas.

3.1 Monopole Design - Reference Structure of a Printed Simple Monopole

In this section, a printed antenna is proposed to operate within the WLAN frequency band. The antenna consists of a dielectric substrate material. The selected conductor is an infinitely thin copper padding with conductivity of $5.8\text{x}10^7$ S/m, with a metalized ground plane on the opposite face. The dimensions are 3.317 mm by 38.85 mm with a ground plane of 33.5 mm and 45 mm. The feeding is done through a microstrip of 50Ω connected to the tip of the patch. This is connected to the edge of the patch in order to modify the width of the patch to yield the impedance that demands, increasing the width decreases the impedance. The patch is placed between the dialectic material with a dielectric constant. In this case it is used Rogers RT5880 with a permittivity of ε_r= 2.2 and a thickness of 0.787 mm. In Figure 21 it is possible to see the design of the antenna structure and the dimensions considered for this design are in [mm].

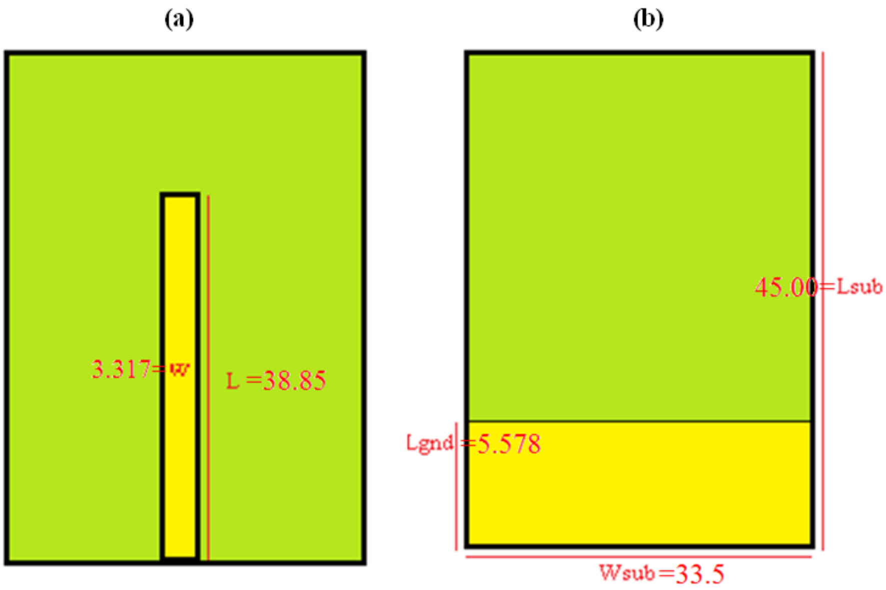

Figure 21: Printed Simple Monopole. Front view(a), back view(b)

We can see from the graphic analysis that, for this proposed monopole, the resonating frequency, is achieved at around 2400 MHz. We can also observe that the impedance response is very close to the resonating frequency, and this is where impedance actually plays its real part, as does resistance. As it is, seen in Figure 22, resistance is very close to 50 Ω while impedance is imaginary, leads to reactance is practically zero.

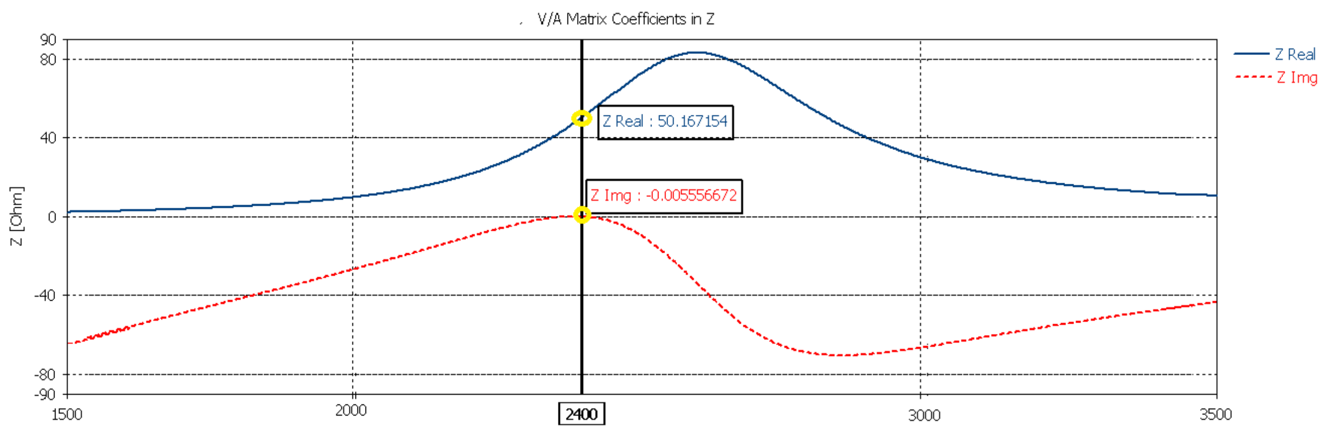

Figure 22: Impedance Real and Imaginary Part of Printed Simple Monopole

In Figure 23, can be observed the S_{11} parameter which is approximately -55.55 dB, at f=2.4 GHz. In the case there is only one point is equivalent to the 'S_{11} Parameter', which is different from 'Return loss'. The bandwidth of the antenna can be extracted from this parameter as the set of frequencies that satisfies the condition $S_{11} < -10$ dB, can see that the bandwidth is between 2250 MHz and 2593 MHz, so is closely 343 MHz, which is good, because the purpose of covering the WLAN band is fulfilled.

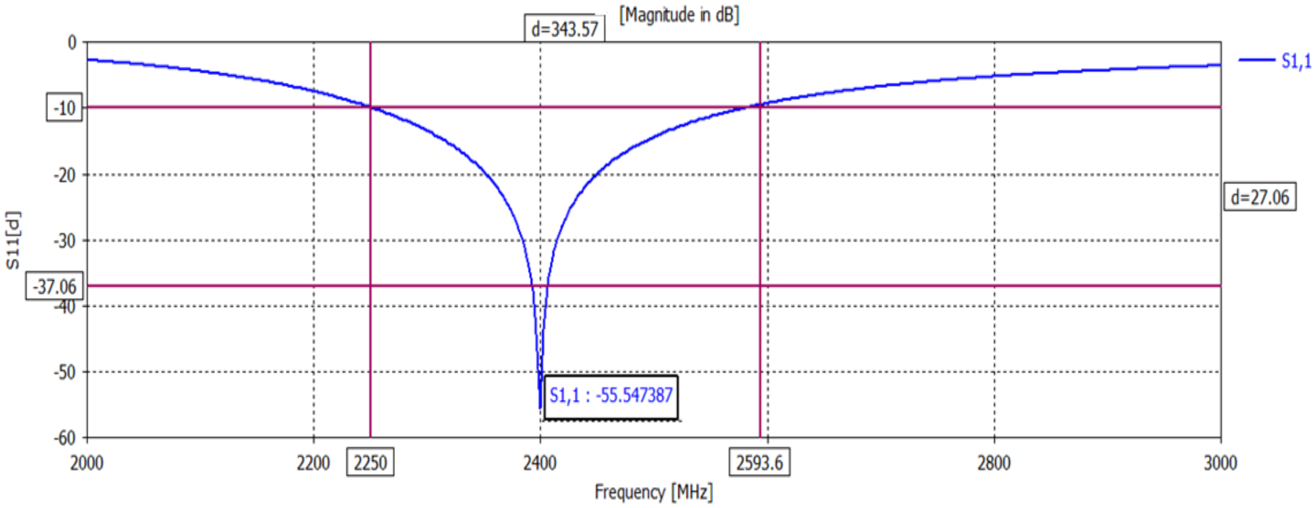

Figure 23: S_{11} Parameter for the Printed Monopole

The radiation pattern of Simple Monopole on YZ plane and XZ plane is present in Figure 24. Such radiation patterns are obtained by numerical simulation for frequencies covered by the antenna, notably up to 2400 MHz, corresponding to the WLAN service.

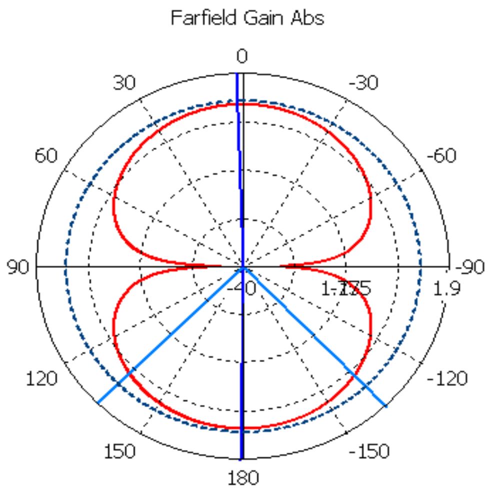

Figure 24: Radiation Pattern of Printed Simple Monopole on YZ plane (solid) and XZ (dashed) at 2400MHz

As can be seen in the previous Figure 24, the radiation patterns are typical of those of a simple monopole. In table 1, are represented the gain, radiation efficiency and overall results for the Printed Monopole. The antenna radiation efficiency is defined as the ratio between the power radiated by the antenna and the accepted power, taking only in consideration any loss by the constituent materials of the antenna. It is also, considered the effect of external objects that interfere with the radiation. The total efficiency is the ratio between the radiated power and the power feed to the antenna, therefore including feeding point.

Parameter	f= 2400 [MHz]
Impedance Real Part [Ω]	50.167
Impedance Imaginary Part [Ω]	-0.005
S_{11} Parameter [dB]	-55.547
Gain [dBi]	1.949
Radiation Efficiency[%]	99.8%

Table 1: Results and gain efficiencies for a Printed Simple Monopole at 2400 MHz

3.2 Changed Structure to Printed L-Monopole

In order to study the versatility of the structure, it was made variations in height and size of the monopole, so that the printed L-monopole and the changed one occupy a smaller area due to the curved arm. This kind of antenna consists of a patch on a same dielectric substrate material of the previous antenna. The area of this antenna is 12.0 mm x 33.85 mm while the total area of the antenna plus the feeding line and support structure is of 33.5 mm x 45.0 mm. The feeding is done through a microstrip line, connected to the edge of the patch. In Figure 25 it is possible to see the design of the antenna structure and the dimensions considered for this design are in [mm].

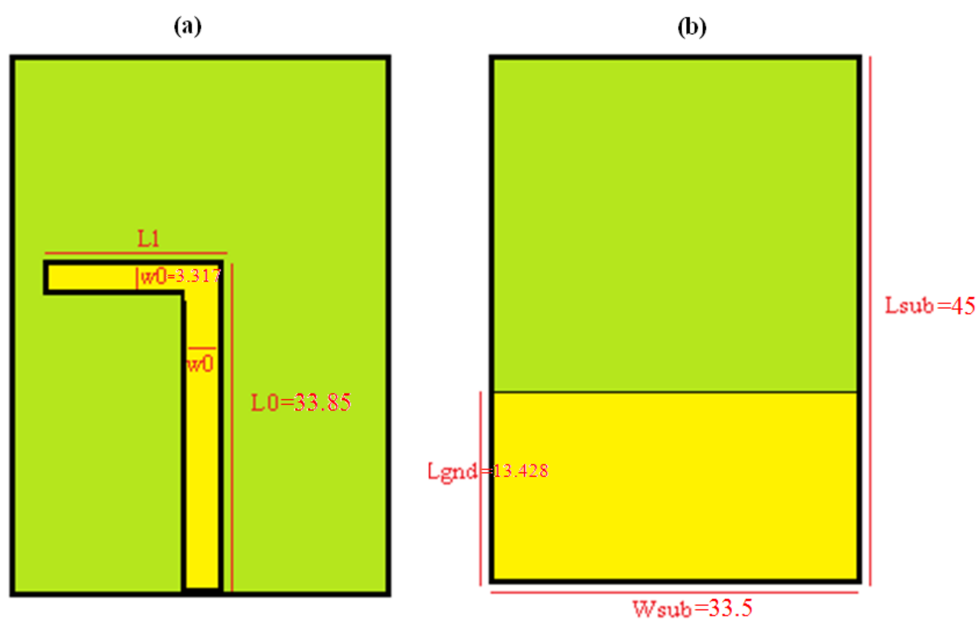

Figure 25: Printed L-Monopole. Front view (a), back view (b)

This Printed L-Monopole was designed to work at the same frequency as the previous Simple Monopole Antenna, and we can observe that the impedance response is very close to the resonating frequency, where the resistance is very close to 50Ω, while the reactance is practically zero, as can be seen in Figure 26.

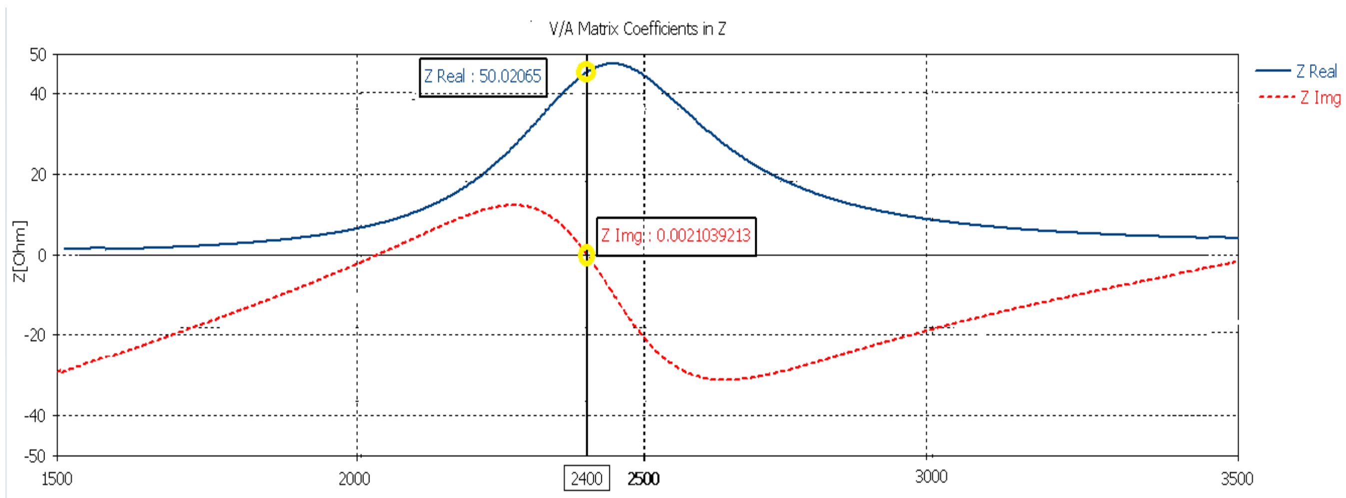

Figure 26: Impedance Real and Imaginary Part for the Printed L-monopole

Also, for the same frequency, as is presented in Figure 27, the S_{11} Parameter is approximately -73,66 dB. Is possible to extract the -10dB bandwidth, which is closely to 305 MHz and that is slightly smaller than the example shown in the previous antenna.

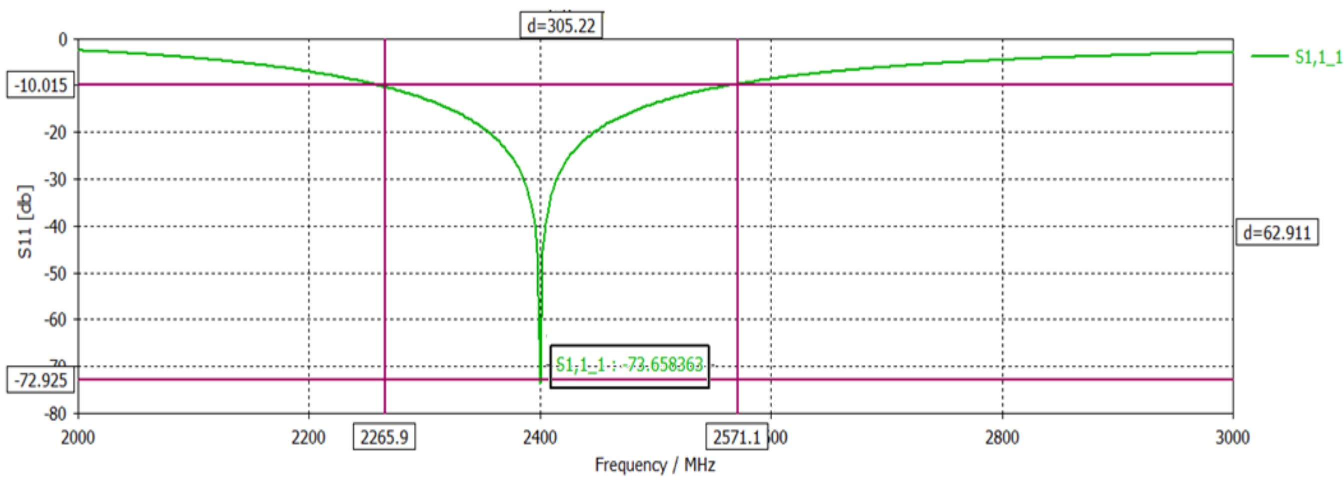

Figure 27: S_{11} Parameter for the Printed L-Monopole

In Figure 28, is shown the radiation pattern numerically obtained. We can see the radiation pattern of Printed L-Monopole on YZ plane and XZ plane also in the same Figure. The bended arm of the monopole has a very small effect on the radiation pattern and this result in an omnidirectional characteristic like the Printed Simple Monopole. However, the gain obtained by simulation for this monopole is higher.

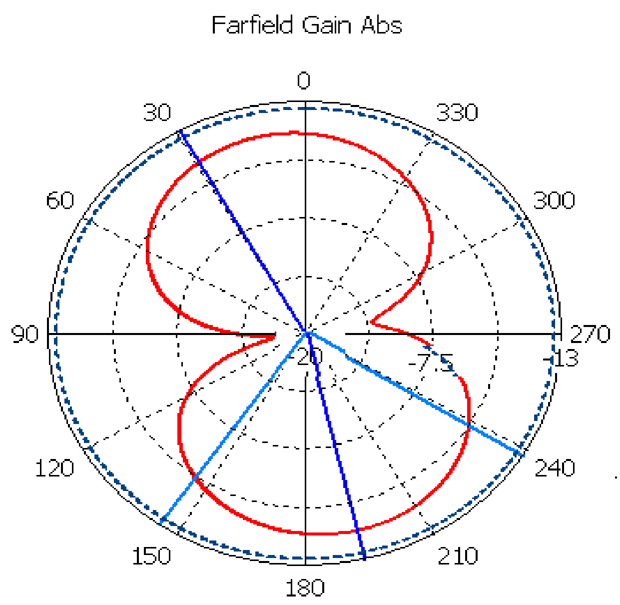

Figure 28: Radiation Pattern for the Printed L-Monopole on YZ plane (solid) and XZ (dashed) at 2400MHz

In table 2, we present the resume of the previous Figure s, like the gain, radiation efficiency and overall efficiency for WLAN.

Parameter	f=2400 [MHz]
Impedance Real Part[Ω]	50.020
Impedance Imaginary Part [Ω]	-0.002
S_{11} Parameter[dB]	-73.65
Gain [dBi]	2.052
Radiation Efficiency [%]	99.8%

Table 2: Results and gain efficiencies for the Printed L-Monopole at 2400 MHz

3.3 Changed Structure to Printed C-Monopole

In order to continue to study on the versatility of the structure the height and size of the monopole had to suffer a change into a Printed C-Monopole, which has a different length when comparing the short version with a long version. These have the advantage of having an even smaller form factor, although the electrical area of the antenna remains the same. In Figure 29, it is possible to see the design of the antenna structure and the dimensions considered for this design are in [mm].

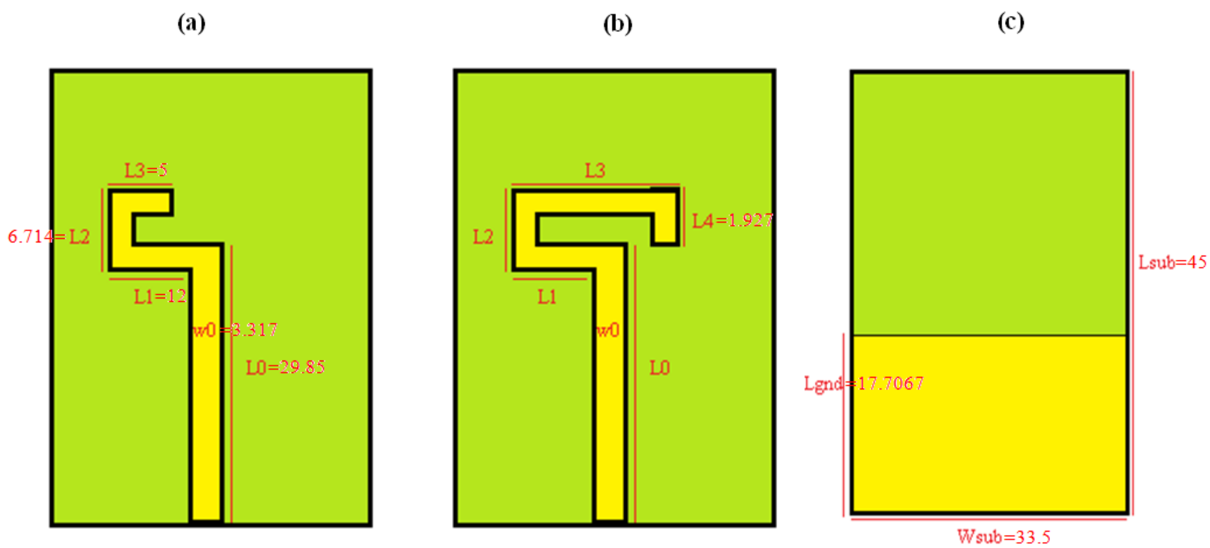

Figure 29: Printed C-Monopole. Front view, Short (a) and Long (b) Versions, and back view(c)

The S_{11} Parameter of Printed C-Monopole Short and Long is closely related to the impedance variation of the antenna, and the value of the impedance is closest to that associated to a resistance of 50, and a reactance of zero. In Figures 30 and 31 we can observe values of -73 dB for S_{11} in the Short Version and of -50 dB, S_{11} in the Long Version.

It is possible to conclude that the absolute bandwidth is very similar for both monopoles because they have a bandwidth of approximately between 2.2 GHz and 2.6 GHz.

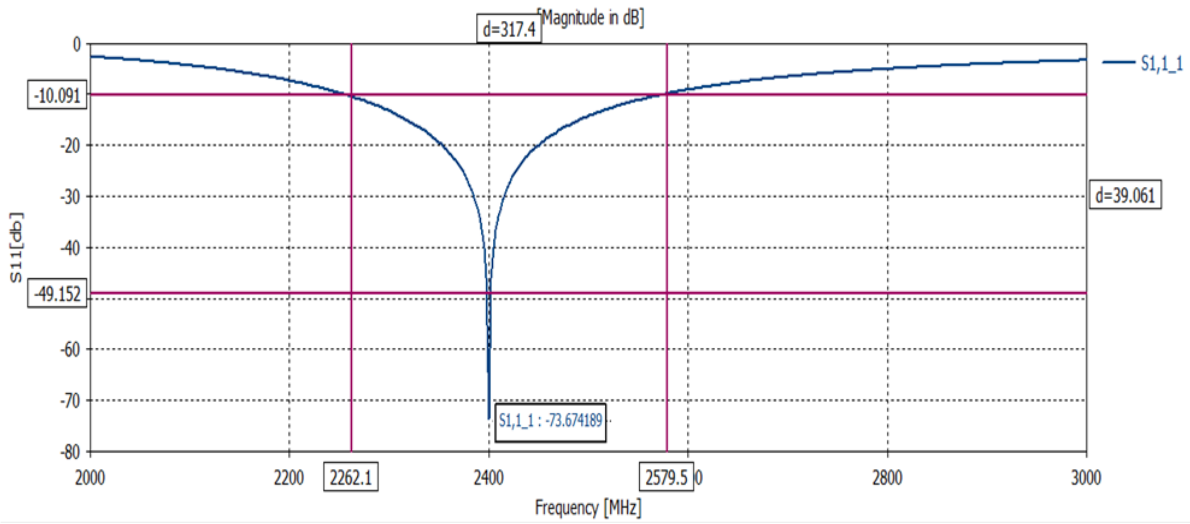

Figure 30: S_{11} Parameter for the Short Printed C-Monopole

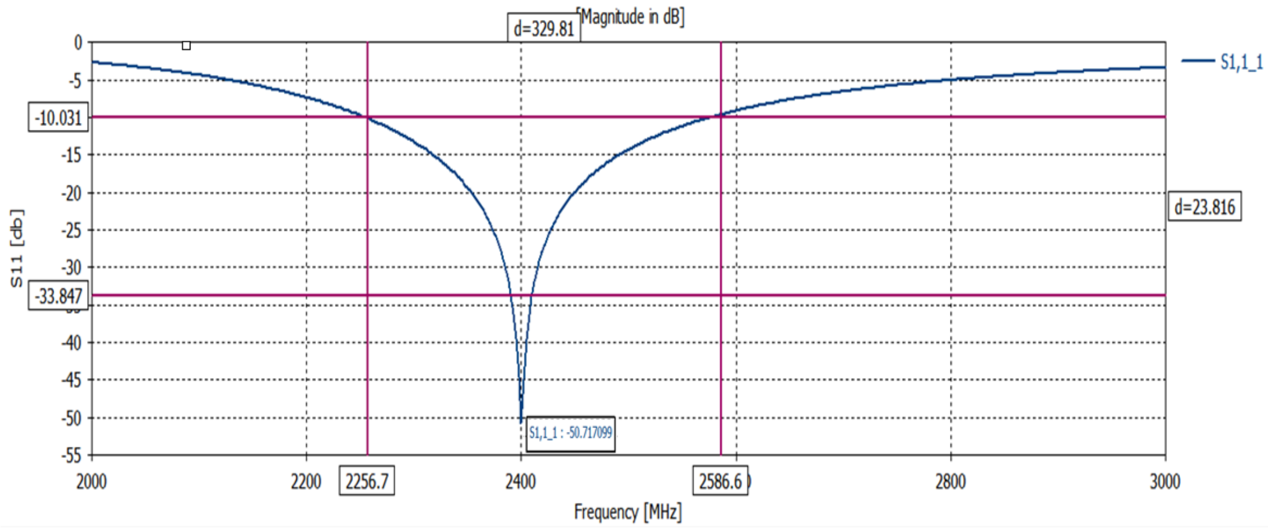

Figure 31: S_{11} Parameter for the Long Printed C-Monopole

From the Figures 32 and 33, we can see the impedance response for Printed C-Monopole, Short and Long respectively, and it shows that impedance's real part is very close to 50 Ω and the impedance's imaginary practically goes from zero in to 2400 MHz.

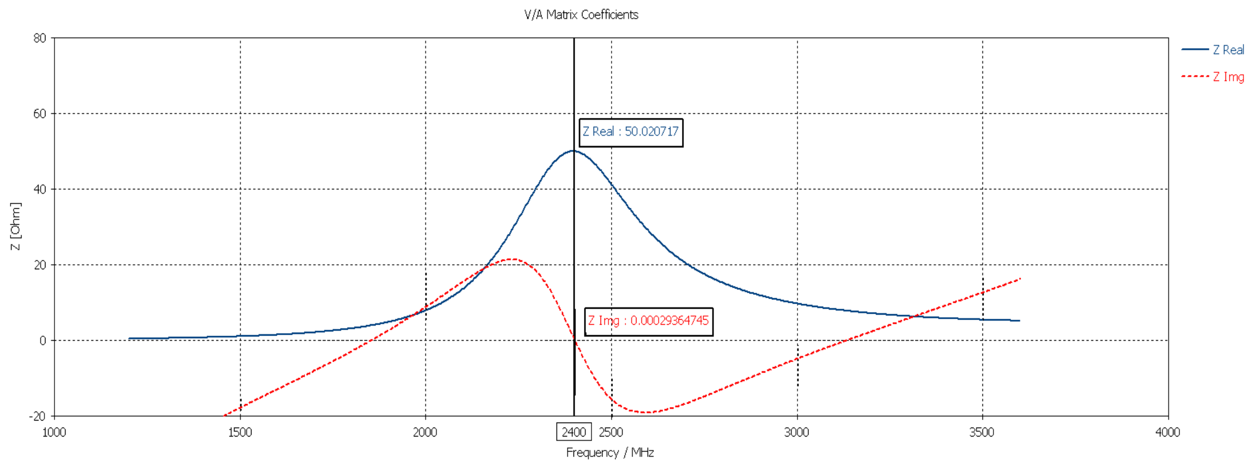

Figure 32: Impedance response for the Short Printed C-Monopole

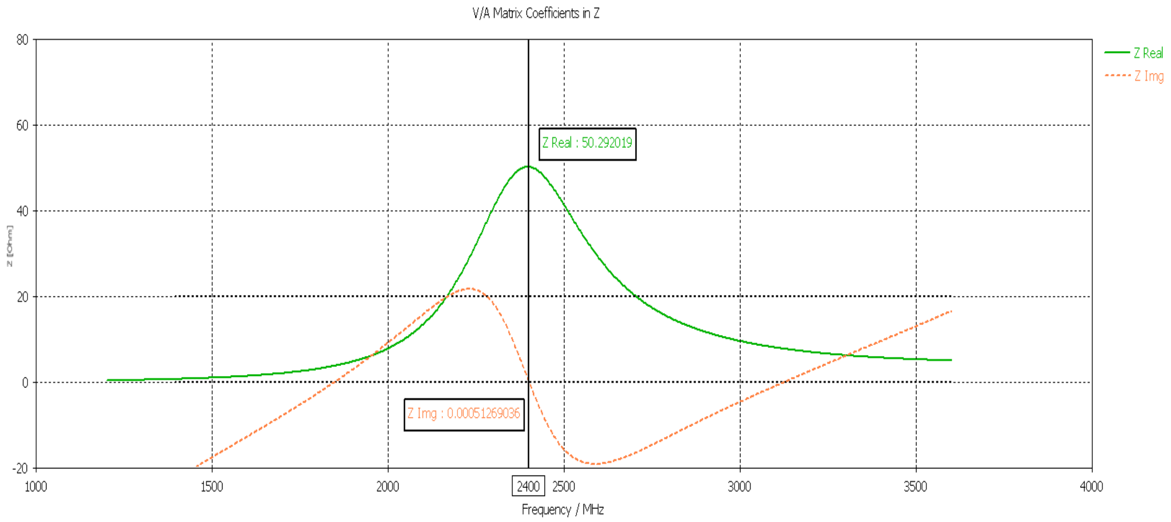

Figure 33: Impedance response for the Long Printed C–Monopole

Therefore, observing this impedance response, it is clear that the monopole has to have a smaller length so that the meander line will result in a bigger overall volume of the antenna.

In Figure 34 presented the radiation pattern for the longer version and we got Gain=2.270 dBi. In relation to the short version for the antenna frequency coverage up to 2400 MHz, we got Gain=2.272 dBi as can be seen in Figure 35. To notice seen the earning that is practically the same.

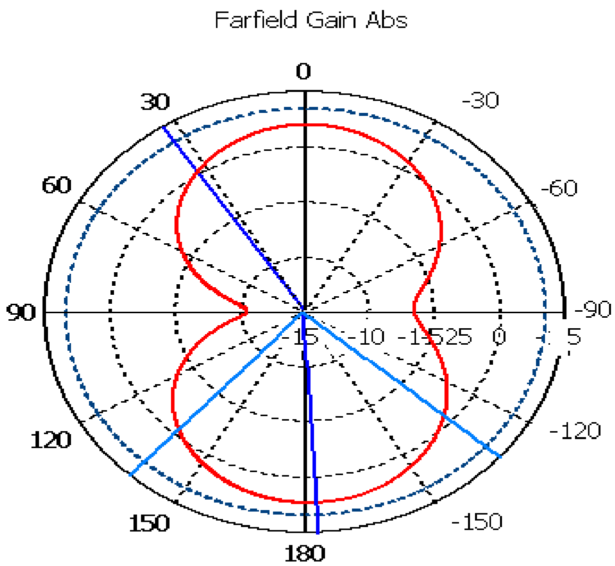

Figure 34: Radiation Pattern for the Long Printed C-Monopole on YZ plane (solid) and XZ (dashed) at 2400MHz

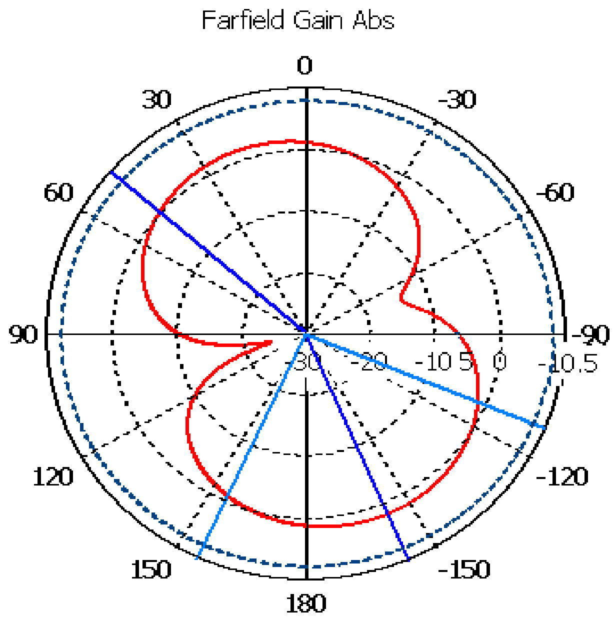

Figure 35: Radiation pattern for the Short Printed C-Monopole on YZ plane (solid) and XZ (dashed) at 2400MHz

For both versions of this monopole the radiation pattern is an issue, because it no longer poses a seemingly perfect 'donut' shape, instead has an increased directivity through certain angles, as can be observed in Figures 34 and 35. This behavior can occur due to different reasons, one of them being the size and proximity of the ground plane to the radiator element, and because of the meander line type structure.

In table 3 presents the summary of the previous Figure s, like the impedances, return loss, gain, radiation efficiency and overall efficiency for the Printed C-Monopole.

Parameter	**f=2400 [MHz]**	
	Short	**Long**
Impedance Real Part[Ω]	50.020	50.29
Impedance Imaginary Part [Ω]	0.00029	0.00051
S_{11} Parameter [dB]	-73.67	-50.71
Gain [dBi]	2.272	2.270
Radiation Efficiency[%]	99.7	99.7

Table 3 Results for the Printed C-Monopole, Short and Long versions at 2400 MHz

3.4 Monopole Design with a Pin Diode

The antenna proposed uses a PIN Diode, to achieve reconfigurability of the antenna. The equivalent diode model, according to [43], can be modulated by a coil and a series resistance when forward biased, and an inductor in series with a parallel of a resistor with a capacitor, when reverse biased, as was illustrated in Figure 12.

I. Reference Structure

The proposed antenna is a C-Monopole printed, only using a PIN diode to make the reconfigurable structure, and contain it in the smallest possible area on Arlon CuClad 217 with 0.787mm thickness, a relative permittivity (ε_r) of 2.17 and a loss tangent (δ) of 0.0009. The actuator used to create the reconfigurability was a PIN diode of AvagoTechonologies [44] with the reference HSMP-3860 and the values of the parasitic capacity and inductance of the diode are essentially constant and independent of power polarization. However, the resistance value does depend on this, and is greater the lower the current. The chosen PIN diode has a low serial resistance, R_s=3.8Ω, with lower forward bias current I_F=1mA. The parasitic capacitance depends on the reverse voltage and frequency, and for frequencies above 1GHz its value has minimal variation. Low capacitance, C_T=0.2pF, $Rs = \frac{12}{If^{0.9}}\,\Omega$. In addition, the L_s is a small value of 1.68 nH. These were the numbers used for the simulations.

The PIN is placed on the upper arm of the monopole location chosen to be based on the simulation. When the diode is reversed biased, the antenna must be resonant to 2.4 GHz. When the diode is forward biased, the antenna must be resonant around 2.05 GHz.

In Figure 36 it is possible to see the design of the antenna structure, C-Monopole with PIN Diode 'OFF' and 'ON'. The dimensions considered for this design are in [mm].

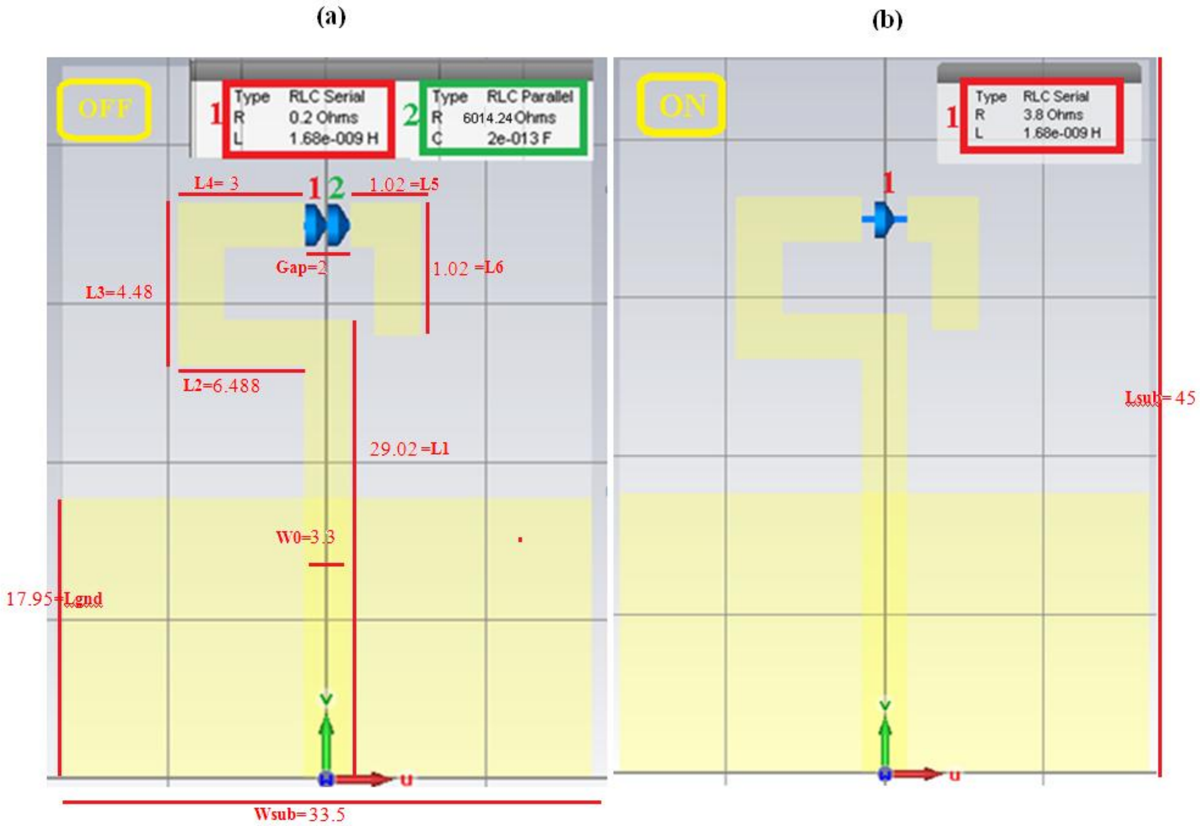

Figure 36: PIN Diode 'OFF' (a) and 'ON' State (b)

The area of the antenna is 33.50 mm x 45.0 mm, and the total area of the antenna plus the feeding line is of 33.50 mm x 44.028 mm. The total length of the monopole, considering the diode in forward bias.

Following the structure previously studied, again on top of the substrate is the monopole as well as the power line that allows impedance matching to 50Ω. At the bottom of the substrate is the ground plane, which covers almost all the bottom side except the area where the monopole is printed, on the opposite side.

The diode activation circuit was considered in the simulated model. Nevertheless, if not considered, this would be another possible source for the obtained deviations in frequency.

The variation of the S_{11} parameter, for both states of the diode, with its frequency and the results of simulation antenna can be observed in Figures 37 and 38. The bandwidth of a printed monopole is related directly, though not exclusively, to the size of the antenna itself. Therefore, the decrease in the size of the antenna helps to explain the decreased bandwidth. With respect to the antenna matching levels, it is based on the previous noticeable Figure s, in the case of antenna with diode differences in terms of adaptation between one band and another they are much more pronounced compared to previously models.

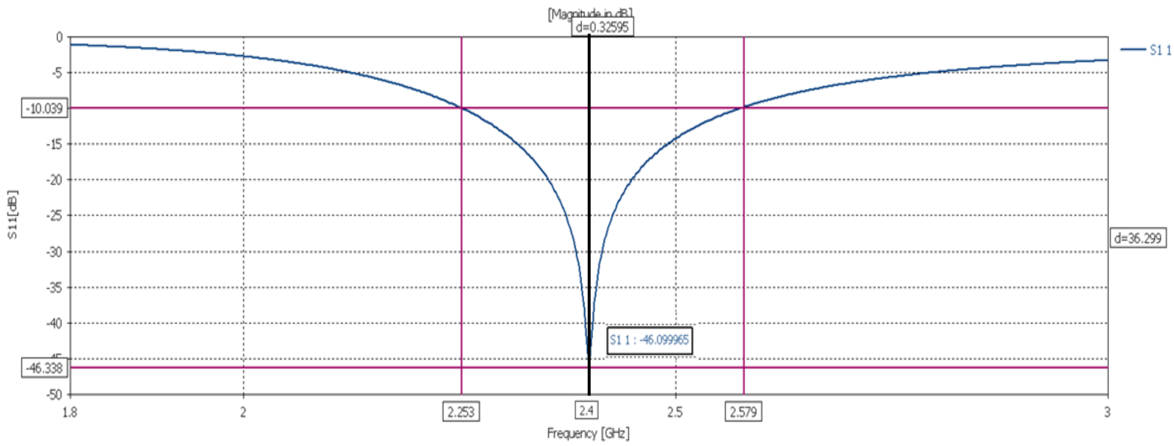

Figure 37: S_{11} parameter for real model of PIN 'OFF state' (Parallel)

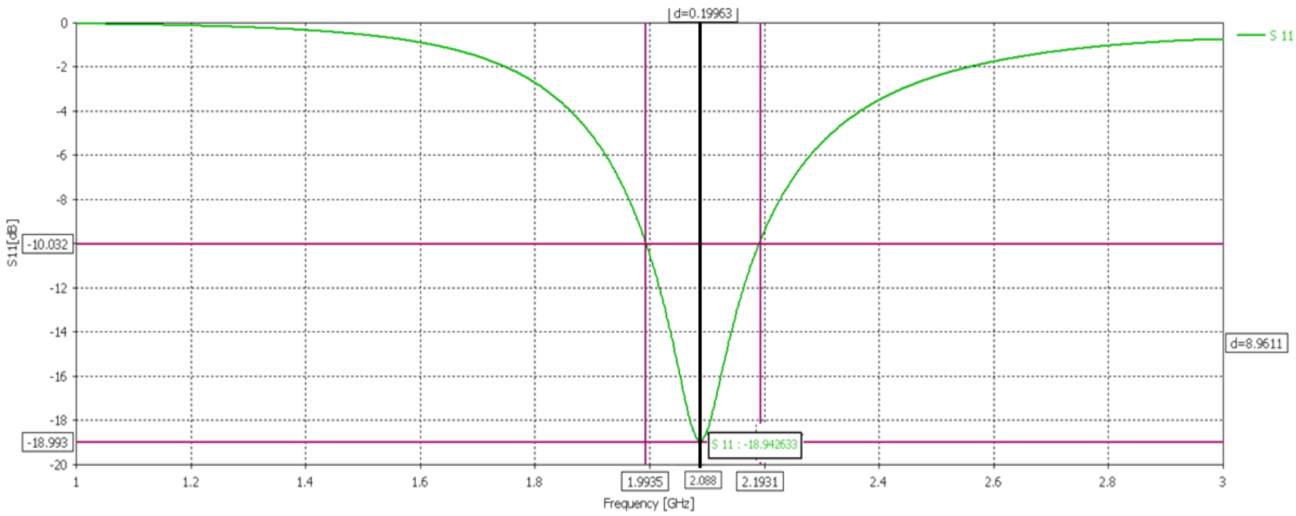

Figure 38: S_{11} parameter for real model of PIN ‘ON state’ (Serial)

Analysing the S_{11} parameter for both states, this has two quite different operating bands, depending on the driving state diode. Presenting a coverage from 2.253 GHz up to 2.579 GHz when the diode is 'OFF'– as shows Figure 37 – and of 1.994 GHz up to 2.193 GHz when the diode is 'ON'– Figure 38.

As stated above, using a microstrip line with a quarter wavelength, it allowed the adaptation of the impedance of the antenna, enabling an adaptation to a given frequency by length thereof and not to a very large bandwidth. In this case, the length of the line is based on the increased frequency of resonance, which leads to a commitment in the design of this line in order to ensure a satisfactory adjustment for both bands operation.

In Figure s 39 and 40 are shown the variation of impedance, in both operating modes, respectively.

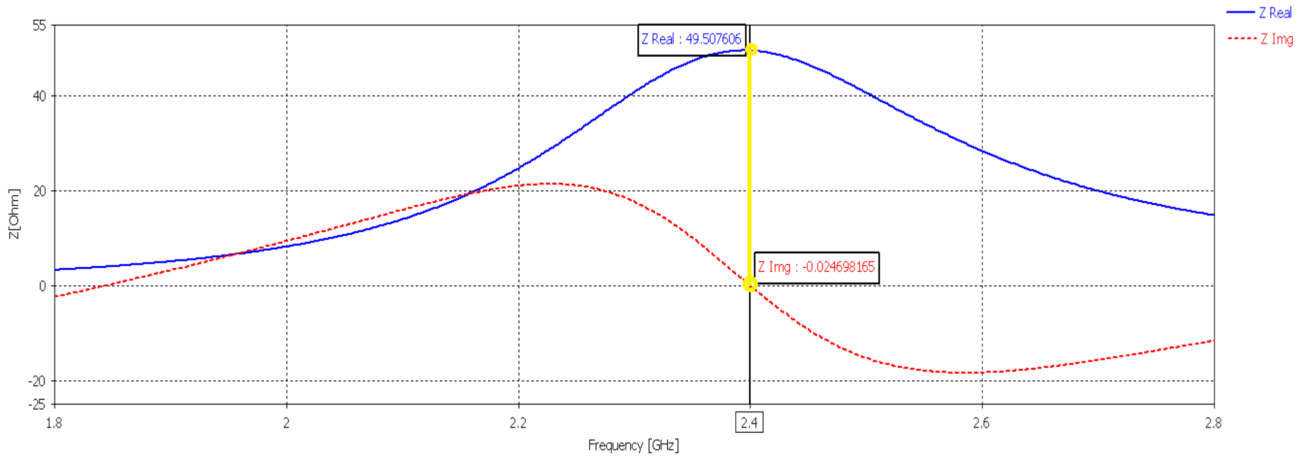

Figure 39: Impedance response for PIN 'OFF state' (Parallel)

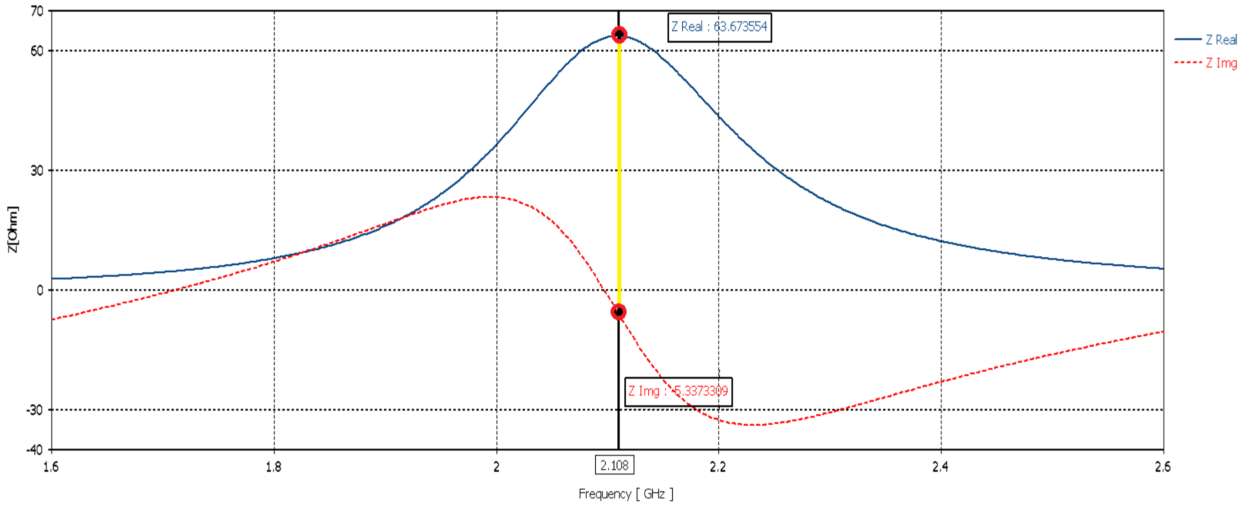

Figure 40: Impedance response for PIN 'ON state' (Serial)

Figure 41 show the comparison between resistances, and in Figure 42, is the reactance comparison in both diodes state. Observing the variation of real and imaginary impedance, we can see a similar response in accordance with the resistive part presenting higher values for lower frequency and lower values for higher frequency.

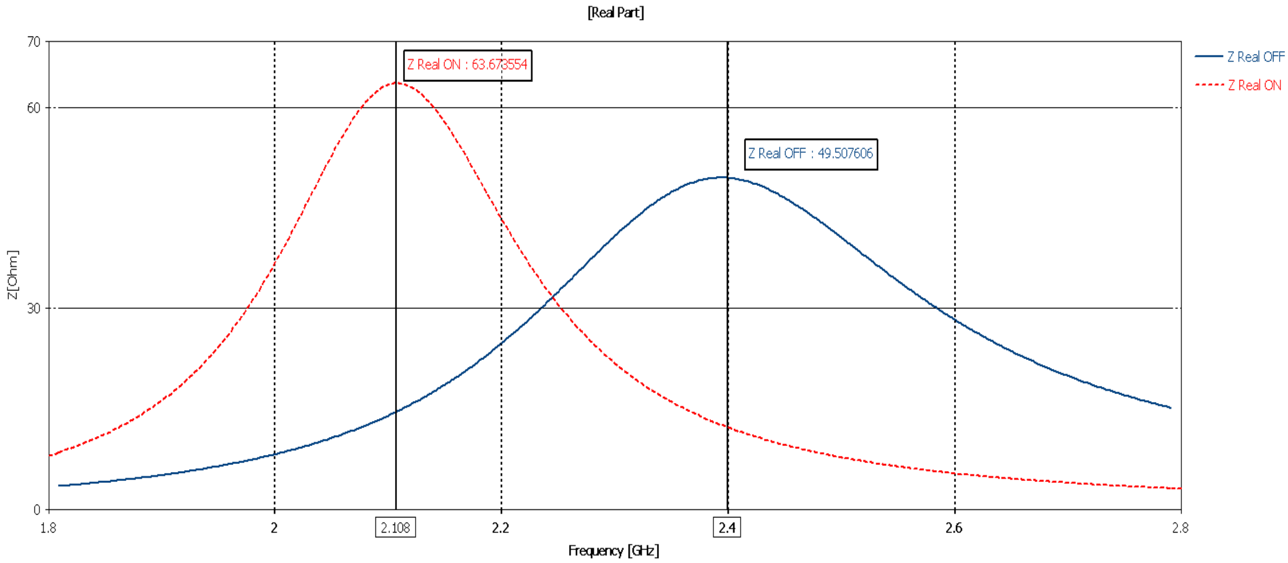

Figure 41: Resistance Comparison

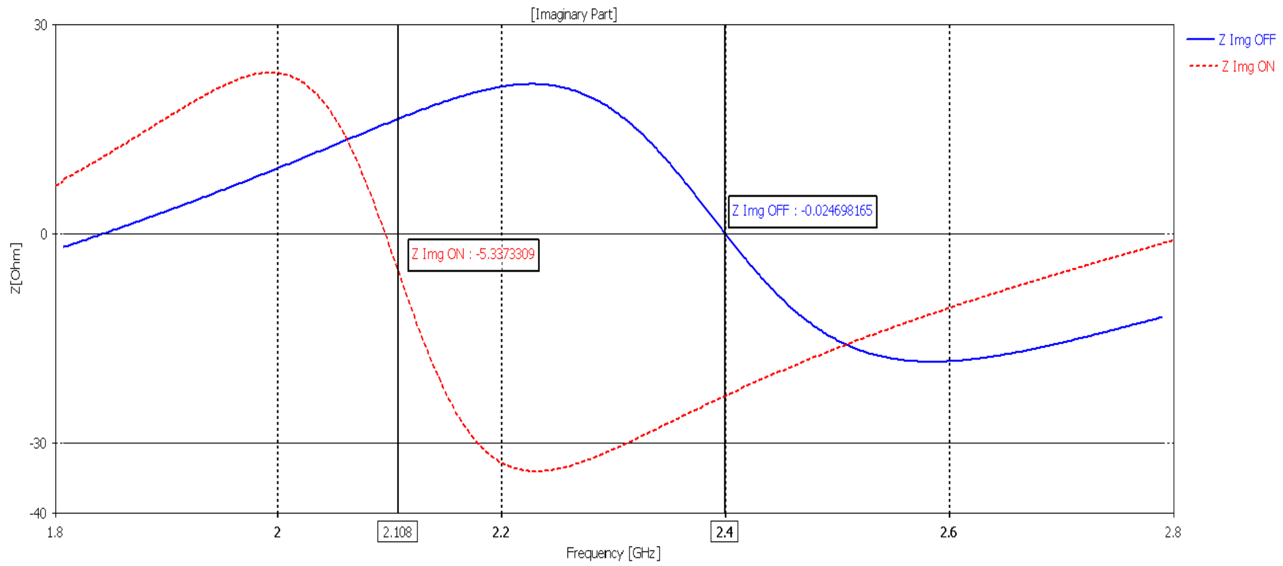

Figure 42: Reactance Comparison

It can also be seen a sharp difference between the two modes, which explains the difference in terms of the obtained S_{11} Parameter, because in this case we reach an impedance which satisfies both modes, which is quite difficult.

In the 'OFF' state, the low value R component will become much larger; to the extent expect the impedance to be dominated by the (parallel) junction capacitance. The junction capacitance of a reverse biased PIN junction is a) lower and b) less bias-dependent than the typical varactor-type behavior observed with the P-N junction. As such, Z equals to LC series, where L is the same as the previous case, and C equals to the junction capacitance.

The resulting radiation pattern from this antenna, is not much different from the previous ones that were referred. It is still omnidirectional, as shown in Figures 43 and 44. The diagram obtained for 2.088 GHz is very similar to the one obtained at 2.4 GHz, which is expected given that the geometry is similar. Despite the similarity, there are differences regarding the gain and efficiency of radiation. The maximum gain obtained for the antenna at higher frequency when the diode is 'OFF' is 2.368 dB, while the gain achieved with the diode in forward bias is 1.950 dB. This means that the diode itself introduces some losses with respect to the antenna gain.

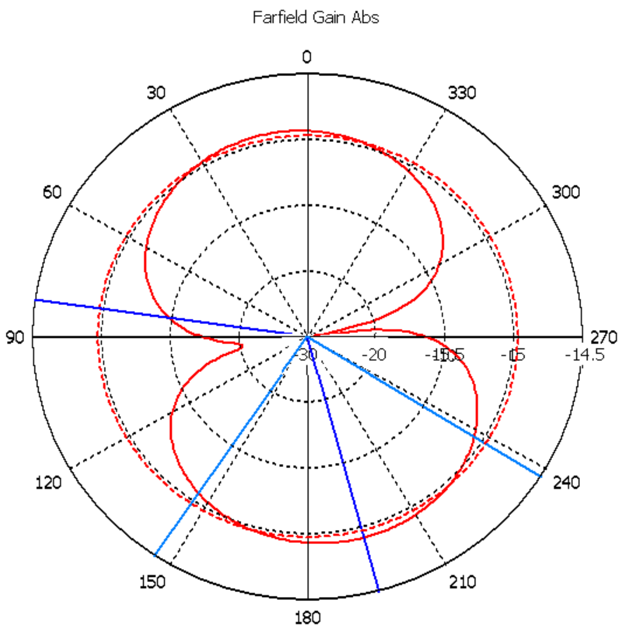

Figure 43: Representation of radiation pattern of PIN 'OFF State' (Parallel) on YZ plane (solid) and XZ (dashed) at 2.4GHz

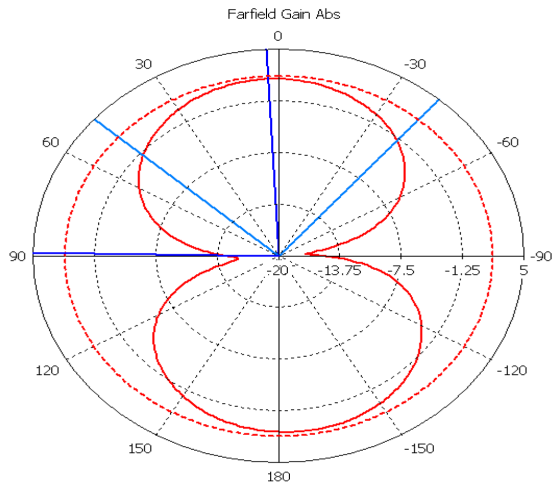

Figure 44: Representation of radiation pattern of PIN 'ON State' (Parallel) on YZ plane (solid) and XZ (dashed) at 2.1GHz

The real difference is significant with respect to gains. The gain decreased considerably in both operating frequencies. This decrease was the in same ratio, of approximately 1.71. Being of 0.97 dBi, at 2.4 GHz and 0.1 dBi at 2.08 GHz. This reduction in gain is result of the product operation mode, in addition to the reduction of the antenna size. It is difficult to conceive, however, until what point this loss is single motivated by PIN. Therefore, the lower gains also lead to a decreased radiation efficiency, which happens in this case presenting values in the range of 80.3% at 2.4 GHz and 77.5% at 2.088 GHz. Although the use of this component leads to a decrease in gains, these have a value range that can be considered acceptable in application for which they are intended.

In table 4 is present a summary of the previous Figure s, like the impedances, return loss, gain, radiation efficiency for the Monopole with Pin Diode.

Frequency [GHz]	**2.4**	**2.1**
Parameter	**‘OFF State’**	**‘ON State’**
S_{11} Parameter [dB]	-46.09	-18.94
Bandwidth of S_{11} Parameter [GHz]	0.33	0.19
Impedance Real Part[Ω]	49.51	63.67
Impedance Imaginary Part [Ω]	-0.03	-5.34
Gain [dBi]	2.37	1.95
Radiation Efficiency[%]	98.5	96.7

Table 4 Results for Monopole with Pin Diode on ‘OFF’ and ‘ON’ State at 2.4 GHz and 2.1 GHz

3.5 Monopole Design with a MOSFET Switch

In addition to the bipolar devices (N-P-N and P-N-P transistors) that have been studied, there are very important unipolar devices called Field Effect Transistors (FET) and is a unipolar device since it functions with the conduction of electrons alone for the N-channel type or on holes alone for a P-channel type. In these devices, the current is associated with the carriage by driving only one type of charge carriers, the majority in this semiconductor region. Among the various types of FETs, the most important, from the point of view of the applications, is the MOSFET . In the MOSFET normally the semiconductor material is silicon, the metallic contacts are of aluminum and the insulator is a silicon oxide (SiO_2).

I. Operating Principle

Figure 45 shows the basic structure of MOSFET . The semiconductor of S_iO_2 isolates the gate terminal. The P-N junction defines a diode between Source and Drain, leading the current when V_{ds} less than zero. The operation principle as a transistor when V_{ds} more than zero.

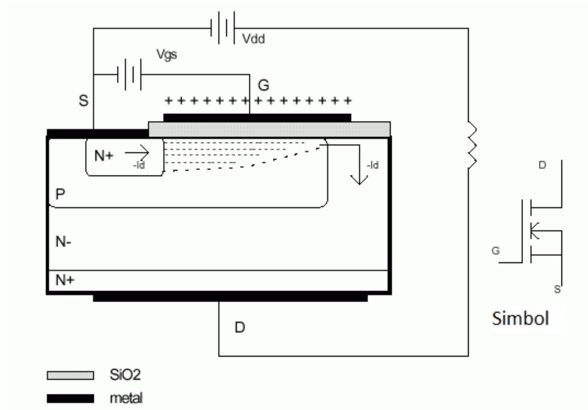

Figure 45: Basic Structure of MOSFET

When a voltage V_{gs} is more than zero is applied, the positive gate potential repels the gaps in the P region, leaving behind a negative charge, but without free carriers. When this voltage reaches a certain threshold (V_{th}) free electrons (generated mainly by thermal effect) in the region P are attracted and form an N channel within the P region, whereby it becomes possible to pass the current between Drain and Source. Raising V_{gs}, more carriers are attracted, expanding the canal and reducing its resistance (R_{ds}), allowing an increased Id. This behavior characterizes the so-called ‘resistive region’.

The passage channel of the I_d produces a voltage drop, which leads to their taper, i.e., the channel, is wider at the border with the N^+ region than when it binds to the N^- region. increased leads to increased voltage drop in the channel and to a greater bottleneck, which would lead to its collapse and extinction of current. Obviously, the phenomenon tends to a point of equilibrium in which the Drain current ‘I_d’ is constant for any V_{ds} characterizing the active region of the MOSFET . Figure 46 shows the static characteristic of the MOSFET .

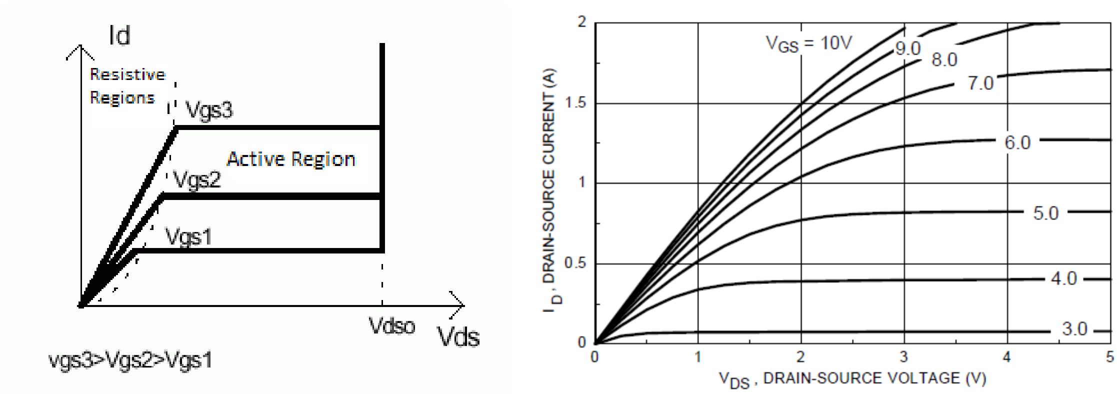

Figure 46: Static Characteristic of the MOSFET and On-Region Characteristics of 2N7000/2N7002/ NDS7002A

A small gate current is required only to charge and discharge the input capacitors transistor. The input resistance is around 10/12 Ω. These transistors are in general N channels, because they have lower losses and higher switching speed due to the greater mobility of electrons in relation to gaps. The maximum V_{ds} is determined by the reverse breakdown diode. The MOSFET s have no second break since the channel resistance increases with the increase of I_d. This facilitates the parallel association of these components. The V_{gs} is limited to a few tens of volts, because of the insulating capacity of the S_iO_2 layer.

3.6 Safe Operating Area

Figure 47 shows the Safe Operating Area of the MOSFET .

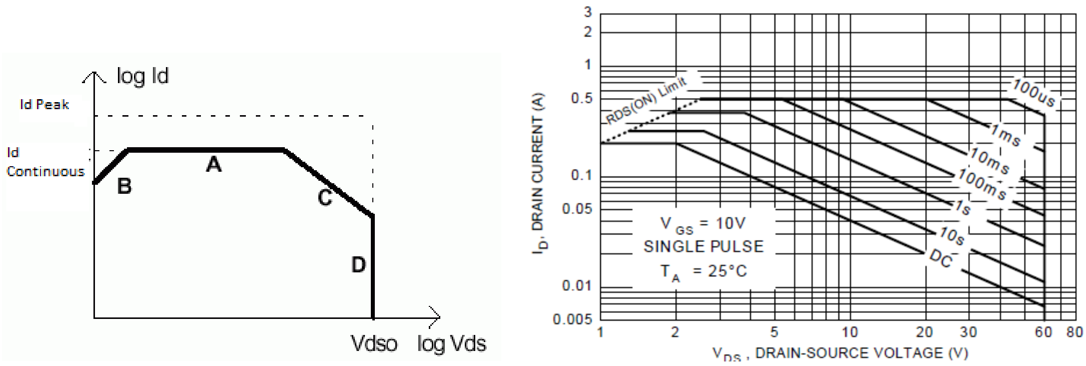

Figure 47: Safe Operating Area on MOSFET 2N7000

For high voltages it is broader than for an equivalent Power Bipolar Transistor (PBT), since there is the phenomenon of second breakdown. For low voltages, however, it has the driving resistance of limitation.

- **A:** Current Maximum Continuous Drain
- **B:** Limit the constant resistance region
- **C:** Maximum power (related to maximum junction temperature)
- **D:** Maximum voltage V_{ds}

3.7 Features Switching

a. Entry into driving

When applying a drive voltage (V_{GG}), the input capacitor begins to charge with a current limited by Resistence Gate (R_g). When it reaches the conduction threshold voltage (V_{th}) after I_d, it begins to increase the drain current. While I_d is lower than I_o, Diode (D_f) remains on driving and V_{ds} is equals to V_{dd}. When Id is equals to Io, D_f off and V_{ds} drops. During V_{ds} reduction there is an apparent increase of the input capacitor (C_{iss}) transistors (Miller effect), causing the change in Gate-to-Source Voltage (V_{gs}) and becomes much slower (due to the 'increase' capacity). This continues until V_{ds} falls when then the V_{gs} voltage increases again, until V_{GG}. In fact, what happens is that, while maintaining a high V_{ds}, the drain current of the capacitor drive circuit is only C_{gs}. When V_{ds} decreases, the condenser from drain and source discharges, the same occurring with the capacitor between gate and drain. The discharge of this latter condenser takes away the current drive circuit, reducing the speed of the charging of C_{gs}, which occurs until C_{gd} is unloaded. All this can be seen in Figure 48.

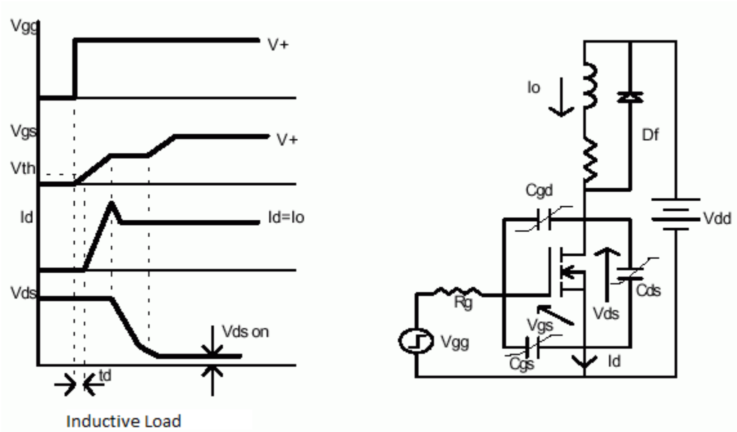

Figure 48: Entry into driving

The datasheet [46] provide information about the transistor with the operating capacitors (C_{iss}, C_{oss} and C_{RSS}), shown in Figure 49, which relates to the component capacitors by:

- ✓ $C_{iss} = C_{gs} + C_{gd}$, with short-circuited CDs
- ✓ $C_{rs} = C_{gd}$
- ✓ $C_{oss} \sim C_{ds} + C_{gd}$

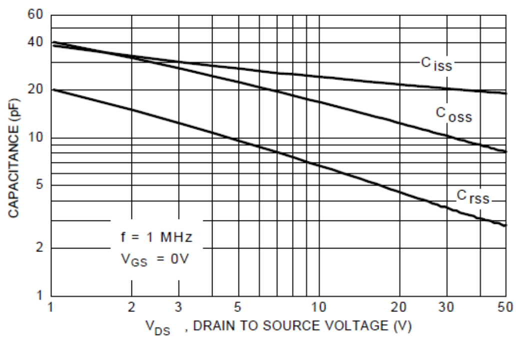

Figure 49: Capacitance Characteristics of 2N7000/ 2N7002 / NDS7002A

b. Shutdown

The shutdown process is similar to that presented but in a reverse order. The use of a negative voltage V_{GG} disengages certain speeds, since it accelerates the discharge of the input capacity. Since MOSFET s have no stored charge, there is no storage time.

3.8 'ON' State Resistance/ Capacitance Trade 'OFF'

For a power MOSFET , on-state resistance is inversely proportional to its active area, while the parasitic capacitances are directly proportional. For the same MOSFET cell structure, a big concern for both device designers and circuit designers is the optimization of tablet size to obtain a better trade-off between smaller on-state resistance and parasitic capacitance, as show in Figure 50.

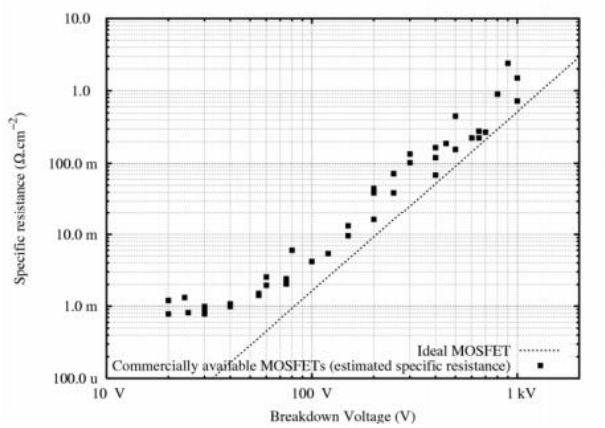

Figure 50: Trade-off between breakdown voltage and specific resistance of power

3.9 Reference Structure

The proposed antenna is again a C-monopole, with the same characteristics of the previous one. The difference is the actuator used to create the reconfigurability, is now a MOSFET based switch.

The first approach is in accordance with that shown in Figure 51 and the related dimensions were considered for this design is in [mm]. The MOSFET was placed on the same place as the Pin Diode, on the upper arm of the monopole. A location chosen based on a simulation, it is possible to see the design of the antenna structure, where is defined a Port 1, in red, Figure 51 and after was draw the 3D schematic between these two ports. Agreeing with [46], the MOSFET can be modulated by an equivalent circuit, shown in Figure 52.

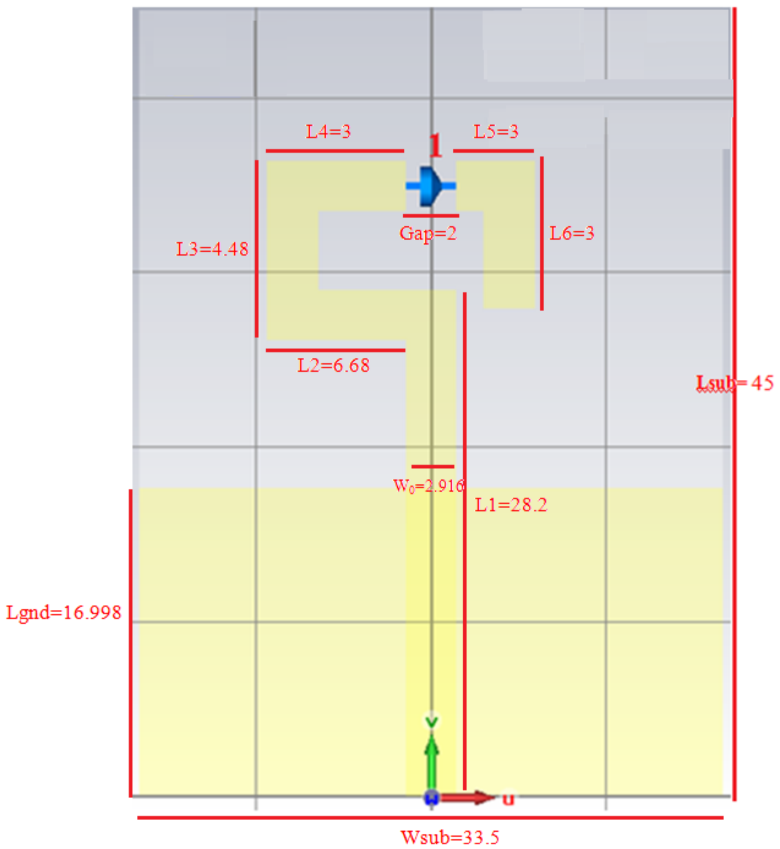

Figure 51: Printed C-Monopole, using a MOSFET as Switch

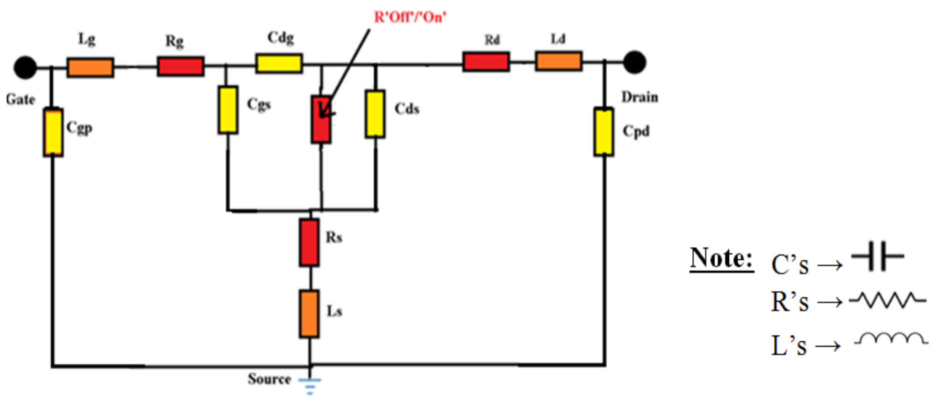

Figure 52: Device equivalent circuit model of MOSFET

Which do a resistance in series parallel to a coil and a resistance also in series with a capacitor and a resistance characterize. A coil and a resistance can simplify this circuit sequentially. The description of device parameters is presented in table 5.

Parameter	Symbol
Source Resistance	R_s
Drain Resistance	R_d
Gate Resistance	R_g
Drain-Source Capacitance	C_{ds}
Gate Pad Capacitance	C_{gp}
Drain Pad Capacitance	C_{pd}
Gate-Source Capacitance	C_{gs}
Gate-Drain Capacitance	C_{gd}
Source Indutance	L_s
Drain Inductance	L_d
Gate Bond Wire Inductance	L_g

Table 5: MOSFET Parameters

The area occupied by the antenna 5.0 mm x 32.68 mm, while the total area occupied by the antenna is 33.50 mm x 45.0 mm.

The antenna proposed in this section uses a component to achieve the reconfigurability of the antenna and in this case is going to use a very popular N-channel MOSFET , the 2N7000 [45]. 2N7000 is an enhancement-type MOSFET , meaning that has more voltage fed to the gate and the current from the drain to the source increases. This is in contrast to depletion-type MOSFET s, in which increasing voltage to the base blocks the flow of current from the drain to the source.

One of the difficulties in the design process is to find the appropriate switch selection. MOSFET is a usual design choice in high frequency switching applications [47]. An important aspect is low on 'ON' State. However, reducing MOSFET 's 'ON' State usually results in an increase in gate capacitance (especially in high switching applications) as well as an increase in gate voltage, which makes switching with TTL levels difficult due to high gate charge (Q_g) and higher gate threshold voltage $V_{gs}(_{th})$. On the other side, decreasing gate capacitance increases the number of times when it rises and falls. Two solutions to the above problem are an appropriate gate drive or a trade-off between parameters for appropriate MOSFET selection.

3.9.1 ‘OFF’ State

When on OFF State, the power of MOSFET is equivalent to a PIN diode constituted by the P^+ diffusion, the N^- epitaxial layer and the N^+ substrate. When this highly non-symmetrical structure is reverse-biased, the space-charge region extends principally on the light-doped side, example, over the N^- layer. This means that this layer has to withstand most of the MOSFET’s ‘OFF’-State Drain-to-Source voltage, as can be seen in Figure 52, where R_{off} =1.5kΩ. According to the datasheet of the 2N7000, the corresponding values of the equivalent circuit to ‘OFF Characteristics’, and is present in table 6.

Parameter	Value
Forward Trans Conductance [S]	100m
Output Capacitance [F]	25p
Zero Gate Voltage Drain Current [A]	1µ
Drain-Source Voltage [V]	48
Gate-Source Voltage [V]	0
Static Drain-Source Off –Resistance[Ω]	$\frac{Vds}{Id} = \frac{48V}{1\mu A} = 48M$
Resistence ‘Off’ [Ω]	1.5k

Table 6: Values to equivalent circuit with MOSFET ‘OFF Characteristics’

Building the Schematic using the CST Studio and using differential ports, testing the differential port in 3D block can be seen in Figure 53.

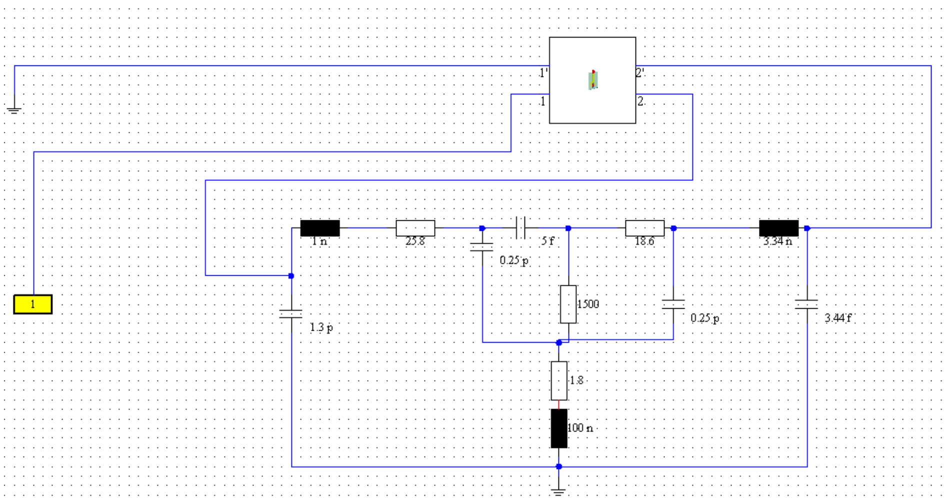

Figure 53: Schematic of 3D block MOSFET 'OFF'

3.9.2 ‘ON’ State

However, when the MOSFET is in the ON-state this N- layer has no function. Furthermore, as it is a lightly doped region, its intrinsic resistivity is non-negligible and adds to the MOSFET 's ‘ON’ State Drain-to-Source Resistance (R_{ON}). Two main parameters govern both the breakdown voltage and the R_{ON} of the transistor: the doping level and thickness of the N- epitaxial layer. The thicker the layer and the lower its doping level the higher the breakdown voltage. On the contrary, the thinner the layer and the higher the doping level the lower the R_{ON}. Therefore, it is a trade-off in the design of a MOSFET , between its voltage rating and its ‘ON’ State resistance [48]. Again building the Schematic using the CST Studio, with a R_{on}=30Ω, and using differential ports, testing the differential port in 3D block can be seen in Figure 54.

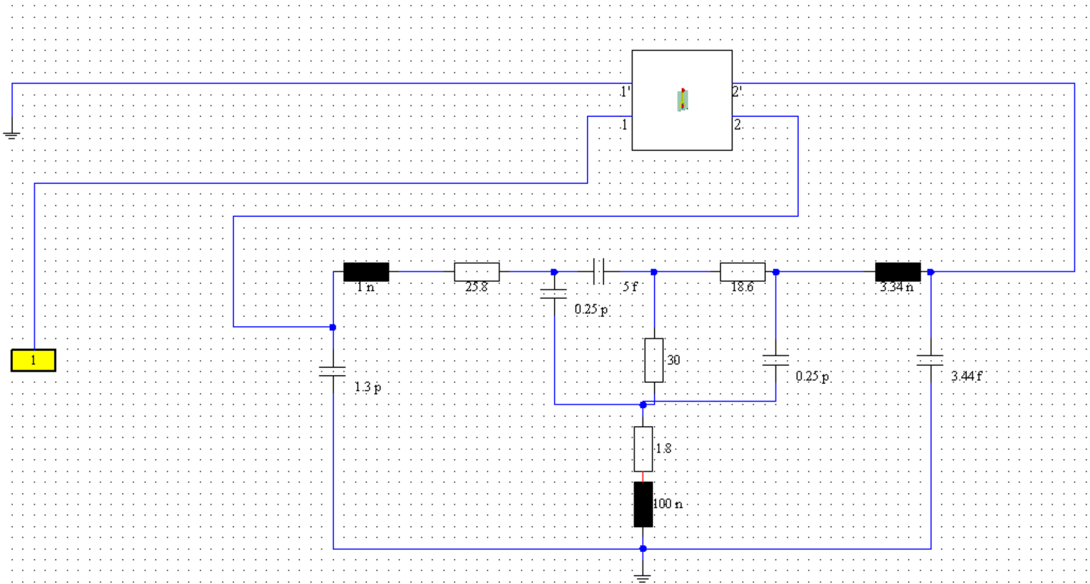

Figure 54: Schematic of 3D block MOSFET 'ON'

Figures 55 and 56 shows the simulated S_{11} Parameter for the proposed monopole antenna, considering the MOSFET in both states. It shows values S_{11} ‘OFF’ of -49 dB and S_{11} ‘ON’ of -35 dB. As it was done in previous analysis, the impedance matching is done with a quarter-wavelength microstrip line, which is designed for the highest frequency of operation, resulting in a higher return loss for the lowest operation band. This line was adjusted based on the numerical simulation so that both frequencies could present satisfactory result.

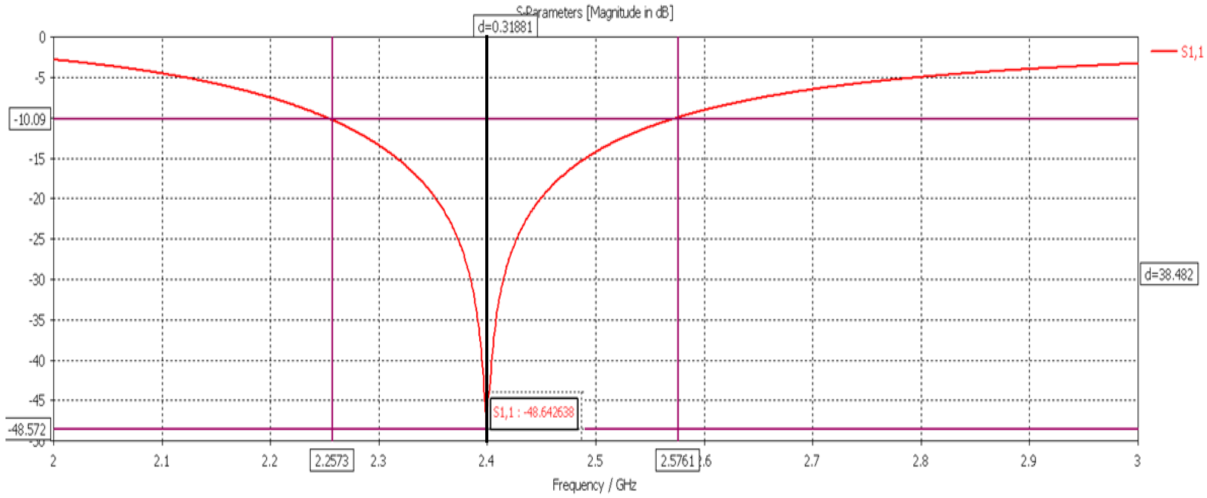

Figure 55: S_{11} Parameter of real model for the 'OFF State'

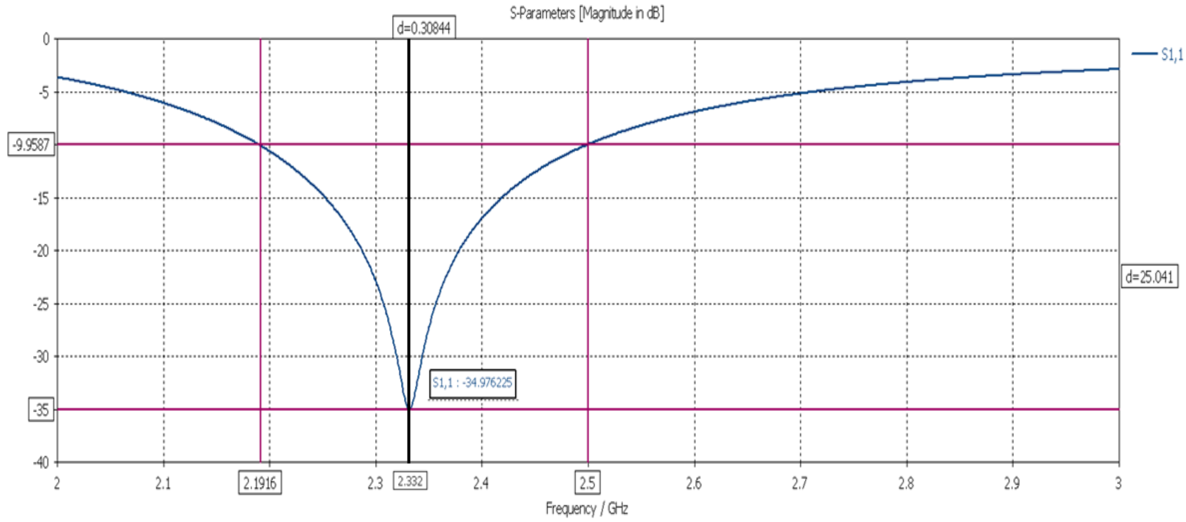

Figure 56: S_{11} Parameter of real model for the 'ON state'

The simulated results presented in previous Figures presents, a bandwidth from 2.25 GHz to 2.57 GHz when the MOSFET is 'OFF', and from 1.83 GHz to 1.95 GHz when the MOSFET is 'ON'. This means that it can nearly support UMTS bands, since these are located between 2.19 GHz to 2.5 GHz. In addition, it can support WLAN service since this band is defined between 2.4 GHz to 2.5 GHz. The measured results present a difference to the simulated numerical results, in particular the 'OFF' band is good while the 'ON' band is shifted, falling below the UMTS band.

Concerning the radiation characteristics, we realized there was pattern in the radiation measurement for the MOSFET 'OFF' state, as is presented in Figures 57, for the YZ/XZ -

planes. The prototype when 'ON' is presented in Figures 58, for YZ/XZ -planes. The results for both states and for the two operating frequencies are these because it is essentially an omnidirectional pattern, as expected since this is a monopole antenna.

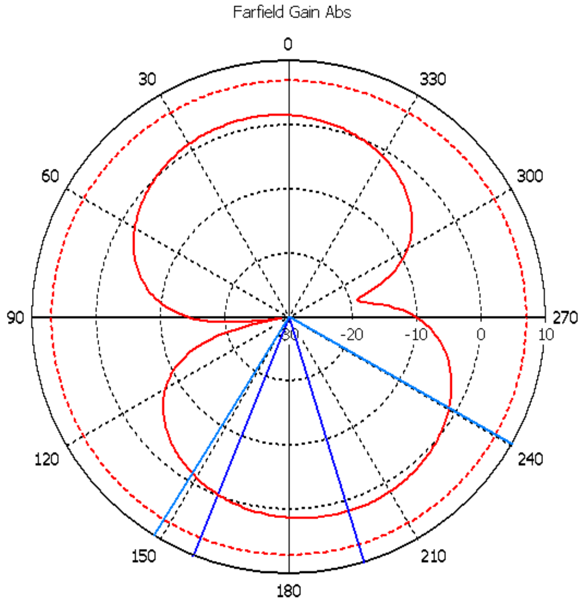

Figure 57: Representation of radiation pattern of MOSFET 'OFF State' on YZ plane (solid) and XZ (dashed) at 2.4GHz

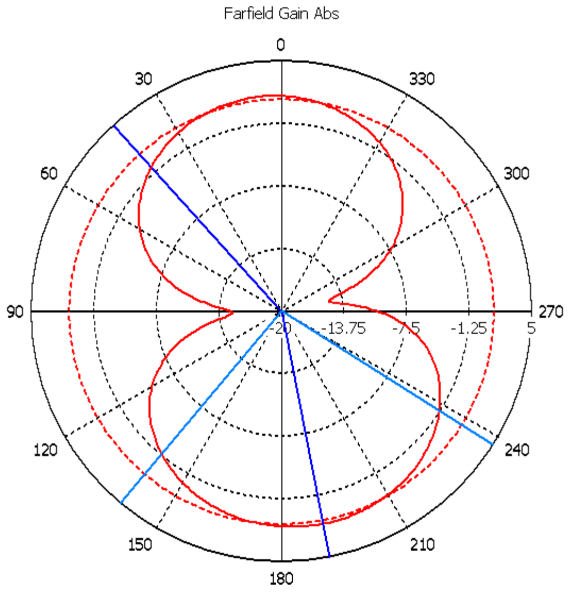

Figure 58: Representation of radiation pattern of MOSFET 'ON State' on YZ plane (solid) and XZ (dashed) at 2.3GHz

The gains are also quite good, with a maximum gain of 2.418 dBi for the higher frequency and 2.397 dBi for the lowest frequency of operation. These gains are also associated with a simulation result of nearly 99% radiation efficiency, which recognizes very good radiation efficiency according to the simulations.

Overall, the results are quite good. Still some optimizations could be made in order to show a better agreement and, of course, could support the proposed services. In table 7 is the resume, like the impedance's, return loss, gain, radiation efficiency and overall efficiency for the Monopole with MOSFET Switch.

Frequency [GHz]	**2.4**	**2.3**
Parameter	**'OFF State'**	**'ON State'**
S_{11} Parameter [dB]	-48.643	-34.976
Bandwidth of S_{11} Parameter [GHz]	0.318	0.308
Gain [dB]	2.418	2.397
Radiation Efficiency[%]	99.8	99.8

Table 7: Results for MOSFET on 'OFF' and 'ON' State at 2.4 and 2.3 GHz

Chapter 4

4. Conclusion

Reconfigurable antennas have the ability to change parameters in accordance with the changing environment. The frequency and radiation pattern reconfigurability are not easily separated in the same system.

In this dissertation, focus was given to frequency reconfigurable antennas and this kind of reconfiguration has its own advantages and disadvantages. Essentially, the reconfigurable antenna pattern operates in frequencies that vary while keeping the same radiation and having no changes in polarization. The reconfiguration of polarization is set (switches and material changes) by keeping constant or unchanged the frequency and radiation pattern. In multi/reconfiguration the compound in both frequency and radiation can be changed while keeping the polarization.

Throughout this project, several printed monopoles were presented as being reconfigurable to operate in two distinct bands. It was shows one of the monopoles is that it is reconfigurable , the others are monopoles reference, being PIN diodes and MOSFET s effective components to implement switches at high frequencies and to cost effectively create a reconfigurable antenna. However, there are constraints in terms of bandwidth, giving diode or transistor affect the bandwidth in the present values. The Diode and MOSFET capacitance also show a large influence over the resonant frequency and bandwidth because, as was seen, the real and imaginary part of the antenna input impedance response as the capacitance value of the PIN and MOSFET increases. The increased capacitance leads to a resonant frequency reduction and narrower bandwidth. Moreover, the effect of the capacitance on the impedance may lead to considerable mismatches, due to the increased value observed. Besides the variations that were studied show the fact that the components are soldered to the radiating element of the antenna and also the diode and MOSFET polarization circuit, which may not present a perfect DC and RF signal isolation, and might be a possible causes for the antenna detuning.

The dimensions of this type of antenna are complex and involves taking into account all the parasitic component values used. Thus making their practical implementation difficult, as does any variation in terms of capacity diode or resistance, changing the resonance frequencies. In order to improve the antenna characteristics, it would be interesting to explore techniques for increasing bandwidth and/or gain.

These points will continue to be analyzed in next section, regarding future work.

4.1 Future Work

The focus of this thesis was to design a reconfigurable monopole antenna. There are a few antennas like the reconfigurable antenna with a PIN diode or with a MOSFET . Many issues still have not been solved and can be the basis for future investigations. Also, the PIN diode might have some impact on the gain and efficiency of the antennas, and the use of MEMS switches is recommended which has less losses than PIN. Cognitive radio might need antennas to operate at the very low frequency bands. Therefore, designing an antenna with wideband and narrow bands featured for the low frequencies is a great challenge. All the content and conclusions presented in this thesis were based solemnly on simulations. Therefore, it is important to manufacture the proposed antennas in order to establish a comparison between simulation and measurement and provide solid proof of the concept here presented. There is also the possibility to improve this study further, by taking on the challenge of designing polarization or directivity reconfigurable antennas.

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