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Option:Space Telecommunications

Design of a Tri-band Dual-polarized Antenna for 5G Applications

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بسم الله الرحمن الرحيم

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DEDICATION

(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ ...)

With all my feelings of respect, with the experience of my gratitude, I dedicate my award and my joy

I would like to express my deepest gratitude to my mother, my source of inspiration and unconditional support, who has always believed in me and given me the strength to persevere in my studies

Without the shadow of your absence, each success is tinged with sadness, because you are not here to share, I dedicate this trumpet to your eternal memory with the hope that, from where you are, you can feel all the pride, my father

To my dear sisters Manel , Ghanima , Achwak and my nieces Eline and Ryme .

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To my partner Meriem who has accompanied me on this work

To my dear friends

To all the family that I have not mentioned

Boulenouar Louiza

DEDICATION

(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ ...)

To my grandmother,

To my parents,

No dedication can fully express all that I owe them: through their prayers, patience with me, and vigilance, may they find in this work the fruit of their immense sacrifices and the proof of my eternal gratitude.

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I dedicate this thesis to you.

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Abstract

The objective of this work is to design a triband dual-polarized microstrip antenna for 5G applications. To achieve triband functionality. A Vivaldi antenna operating at 2.3-2.4GHz,3.5-3.7GHz,5.8-5.9GHz is designed and by incorporating two resonators, two operating frequencies have been added: 3.5 GHz and 5.8 GHz. In addition, to obtain polarization diversity, the two Vivaldi antennas have been positioned orthogonally to each other. The simulation and parametric studies have been conducted using CST Microwave Studio Suite.

Résumé

L'objectif de ce travail est de concevoir une antenne microstrip tri bande à double polarisation pour les applications 5G. Pour atteindre la fonctionnalité tri bande. Une antenne Vivaldi fonctionnant à 2,3-2,4GHz, 3,5-3,7GHz, 5,8-5,9GHz et en incorporant deux résonateurs, deux fréquences de fonctionnement ont été ajoutées : 3,5 GHz et 5,8-5,9 GHz. En outre, pour obtenir une diversité de polarisation, les deux antennes Vivaldi ont été positionnées orthogonalement l'une par rapport à l'autre. Les études de simulation

Et les études paramétriques ont été réalisées à l'aide de la suite CST Microwave Studio.

ملخص

الهدف من هذا العمل هو تصميم هوائي ثنائي الاستقطاب ثلاثي النطاقات ثلاثي الموجات متناهي الصغر لتطبيقات 5G. لتحقيق وظيفة ثلاثية النطاق. هوائي فيفالدي يعمل على ترددات 2.3-2.4 جيجاهرتز و3.5-3.7 جيجاهرتز و5.8-5.9 جيجاهرتز ويتضمن رنانين، تمت إضافة ترددين للتشغيل: 3.5 جيجاهرتز و5.8-5.9 جيجاهرتز. وبالإضافة إلى ذلك، ولتحقيق تنوع الاستقطاب،تم وضع هوائي فيفالدي بشكل متعامد مع بعضهما البعض.دراسات المحاكاة والدراسات البارامترية باستخدام مجموعة CST Microwave Studio.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

1G	**First Generation**
2G	**Second Generation**
3G	**Third Generation**
4G	**Fourth Generation**
5G	**Fifth Generation**
DCS	**Digital Cellular System**
EBG	**Electromagnetic Band Gap**
FDMA	**Frequency Division Multiple Access**
GPS	**Global Positioning System**
GSM	**Global System for Mobile Communications**
LAN	**Local Area Network**
LTE	**Long-Term Evolution**
LOS	**Line of Sight**
MIMO	**Multiple Input Multiple Output**
mmWave	**Millimeter Wave**
MSA	**Microstrip Antenna**
TDMA	**Time Division Multiple Access**
UMTS	**Universal Mobile Telecommunications System**
WBAN	**Wireless Body Area Network**
WLAN	**Wireless Local Area Network**
WMAN	**Wireless Metropolitan Area Network**
WPAN	**Wireless Personal Area Network**
WWAN	**Wireless Wide Area Network**

General introduction

In the 1950s, a new wave of innovation washed over the field of microwave technology. Pioneering minds like Robert E. Collin and George Gouras envisioned a revolutionary antenna solution – the microstrip antenna. This brainchild offered a compelling alternative to traditional antennas, boasting a compact size, low profile, and seamless integration with the burgeoning technology of printed circuit boards (PCBs). These inherent advantages were a game-changer, perfectly aligned with the miniaturization and mass production demands of the time.

The early microstrip antenna prototypes were relatively simple and limited in performance. However, their ease of fabrication opened doors to large-scale production and integration into compact wireless devices. As research intensified, fueled by the growth of both microwave technologies and wireless communication needs, significant advancements were made. Engineers gained a deeper understanding of the underlying principles governing microstrip antennas, leading to the development of sophisticated design techniques. These techniques enhanced performance in crucial areas like bandwidth, gain, radiation pattern, and efficiency.

The arrival of second-generation (2G) wireless networks in the 1990s marked a turning point for microstrip antennas. These networks demanded compact, low-cost antennas that could operate within specific frequency bands. Microstrip antennas, perfectly suited for these requirements, played a pivotal role in the widespread adoption of 2G technology. This ultimately democratized mobile phones and ushered in a new era of communication, forever transforming the way we connect with each other.

The subsequent development of 3G and 4G networks further solidified the dominant position of microstrip antennas in the wireless realm. Their ability to accommodate wider frequency bands and deliver superior performance made them indispensable for meeting the ever-increasing demands for data capacity and throughput. Today, microstrip antennas are ubiquitous components in a diverse range of wireless systems, from the mobile phones in our pockets to satellite communications orbiting the Earth, radar applications that guide us, and even the wearable electronics that are becoming an extension of ourselves.

This historical journey of microstrip antennas is intricately interwoven with the evolution of wireless networks. Today, we stand on the cusp of the next generation of wireless communication: 5G promises to deliver unprecedented data rates, ultra-low latency, and massive connectivity, revolutionizing industries, enabling new applications, and connecting billions of devices.

The advent of 5G networks introduces significant challenges for microstrip antennas, particularly concerning their ability to handle complex propagation environments and accommodate broader frequency ranges. One of the primary issues is multipath fading, where radio waves reflect off obstacles, leading to reduced reliability and performance of 5G systems. To mitigate this, advanced antenna diversity techniques, such as polarization diversity, have been developed.

Polarization diversity leverages the distinct characteristics of signals received by multiple antennas, optimizing their combination to counteract multipath fading and improve signal quality. This approach is especially beneficial in environments with substantial reflections that can degrade the performance of a single antenna.

This project is focused on designing and simulating a tri-band, dual-polarized microstrip antenna tailored for 5G applications. The goal is to create an antenna that effectively operates across three crucial 5G frequency bands: 2.3-2.4 GHz, 3.5 3.6GHz, and 5.8 5.9 GHz. By incorporating dual polarization, the antenna will enhance signal reception and performance in challenging environments, thus reducing the need for multiple antennas while leveraging the advantages of polarization diversity.

To achieve this objective, the project has been divided into three main chapters:

The first chapter provides an overview of microstrip antennas, including their operating principles and design techniques for multiband and dual-polarized configurations. This foundational knowledge sets the stage for understanding the advanced requirements and innovations needed for 5G applications.

The second chapter examines the evolution of wireless networks towards 5G, detailing different network types, 5G frequency bands, and key components like link budget and propagation channels. This context is essential for appreciating the advancements in antenna technology required to meet the demands of modern wireless communication systems. It also covers multi-antenna systems, MIMO technology, and methods to improve transmission quality.

The third chapter focuses on designing a tri-band dual-polarized antenna using CST software for 5G frequencies (2.4-2.4 GHz, 3.5-3.6 GHz, 5.8-5.9 GHz). It details the design process and analyzes simulation results for bandwidth, gain, and isolation, demonstrating how theoretical and practical considerations are applied to develop a high-performance antenna suitable for 5G networks.

Chapter 1

An overview of microstrip antenna

Chapter 1: An overview of microstrip antenna

1.1- Introduction

To design antennas for 5G applications, engineers must perform a meticulous analysis, considering various parameters to ensure the antenna is compact, low-profile, and capable of multiband transmission.

In this chapter, we will examine the definition of microstrip antennas, their geometry, advantages, and the applications developed using these antennas. We will analyze the techniques employed to achieve multiband antennas, followed by the methods for realizing dual-polarized antennas.

1.2- Geometries of the basic microstrip antenna

The idea of microstrip patch antennas arose from utilizing printed circuit technology not only for the circuit components and transmission lines but also for the radiating elements of an electronic system. The basic structure of the microstrip patch antenna is shown in Figure 5. It consists of area of metallization supported above a ground plane by a thin dielectric substrate and fed against the ground at an appropriate location. The patch shape can in principle be arbitrary; in practice, the rectangle, the circle, the equi-triangle and the annular ring are common shapes [1].

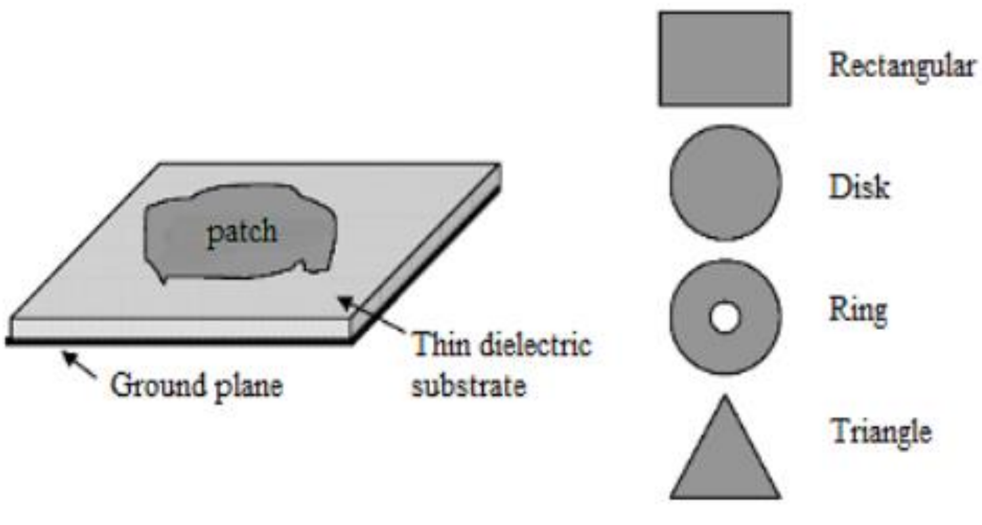


Figure 1: The basic structure of microstrip antenna [1]

1.3- Advantages and disadvantages

1.3.1- Advantages

Microstrip antennas have many advantages, including the following [2]:

1.Low weight

2. Low profile

3. Thin profile

4.low cost

5. Required no cavity backing

6. Multi-band antennas, multi-polarization possible

7.It is possible to achieve both linear and circular polarization by simply shifting the power supply's location.

8. Feed lines and matching network can be fabricated simultaneously

1.3.2- Disadvantages

Microstrip antennas have disadvantages, much like any other technology, including the following [2] [3]:

1. Low efficiency due to dielectric losses and conductor losses compared to Yagi,Dipole antenna. [4]
2. Low gain compared to Dipole antenna .
3. Large ohmic loss in the feed structure of arrays
4. Limited performance by conductor and dielectric losses, and surface waves (higher conductor & dielectric losses for a thin substrate, higher surface wave losses in a thick substrate).
5. Low bandwidth.
6. Low power handling capacity.
7. Excitation of surface waves.
8. Polarization is difficult to achieve.
9. Complex feed structures require high performance arrays.

1.4- Vivaldi antenna:

Vivaldi antennas are often broadband or double-band in the GHz range. P. Gibson named it "Vivaldi" in reference to Antonio Vivaldi, the year of its conception in 1978, marking the composer's 300th birthday [5].

There are three types of Vivaldi antenna:

a) **Tapered slot Vivaldi antenna**: is the original design introduced by Gibson in 1979.It's basically a flared slot line, fabricated on a single metallization layer and supported by a substrate dielectric. The Design of tapered slot Vivaldi antenna is a trade-off between the antenna size and its bandwidth towards low frequency as shown in fig 6 (a) [6].

b) **Antipodal Vivaldi Antenna:** In this case, one "strand" of the antenna is etched on the upper side of the substrate, while the second strand is etched on its lower side shown in figure 6 (b). This topology facilitates feeding, with the use of a coaxial connector, unlike a coplanar Vivaldi antenna (the aperture is engraved on a single side), where it is necessary to adapt the feed [7].

c) Balanced Antipodal Vivaldi Antenna: The balanced and antipode Vivaldi antenna is similar to the previous one but with an extra layer. The orientation of the direction of the slot alternates between the three layers as shown in Fig 6 [5].

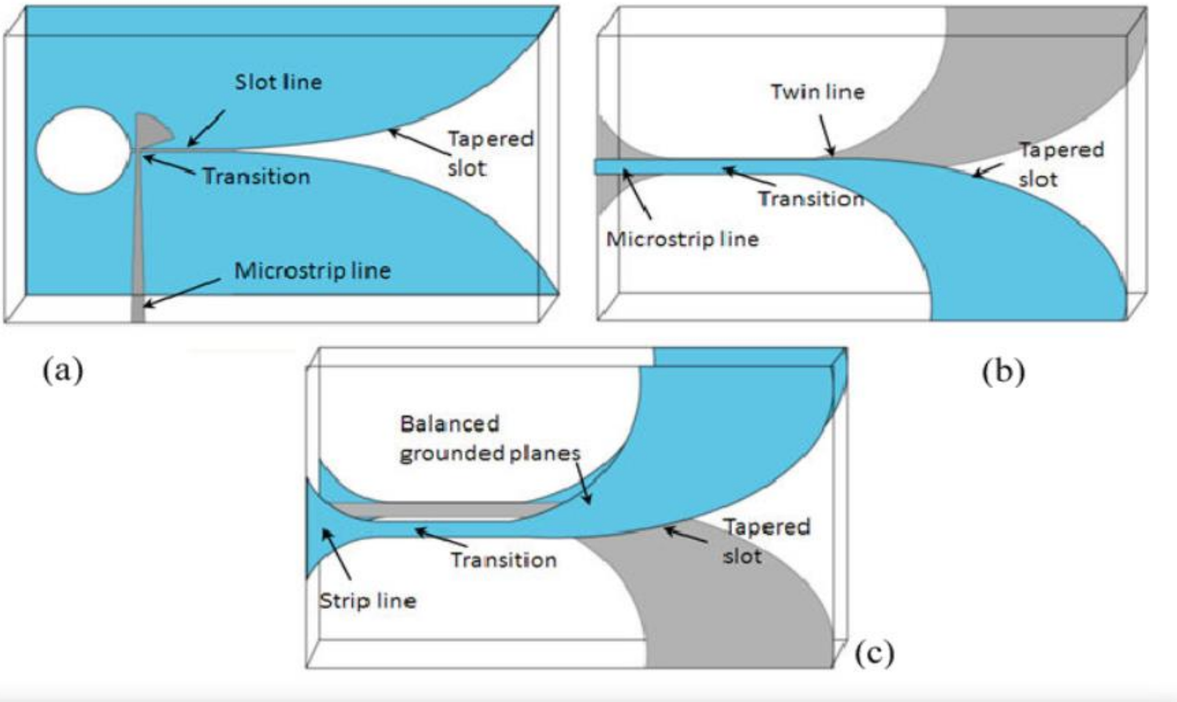


Figure 2:(a)-Tapered slot Vivaldi antenna, (b)-Antipodal Vivaldi antenna, c)-Balanced antipodal Vivaldi antenna [6]

1.4.1 Half Vivaldi

The Half Vivaldi antenna is an innovative variation of the traditional Vivaldi antenna. This antenna stands out for its ability to maintain a wide bandwidth and good radiation performance while being designed to take up less space [8]. Ideal for environments where compactness is essential, the Half Vivaldi antenna offers significant advantages in various applications such as: Medical Imaging, Ultra-Wideband systems, Ground Penetrating Radar.

1.5- Feed methods

There are several techniques for feeding the microstrip antennas and they may be divided into two categories: non-contacting and contacting feed strategies.

The four most popular are the microstrip line, coaxial probe, aperture coupling, and proximity Coupling. [9]

1.5.1- Microstrip line feed

In this type of feed, a microstrip line is connected directly to the edge of the radiating element (Figure (7)). The width of this line is smaller than that of the patch. The advantage of this type is that it can be engraved on the same side as the radiating element, it is easy to manufacture, and simple to adapt to the resonance. It is one of the most widely used techniques in printed antennas, it has the disadvantage of generating parasitic radiation. [10]

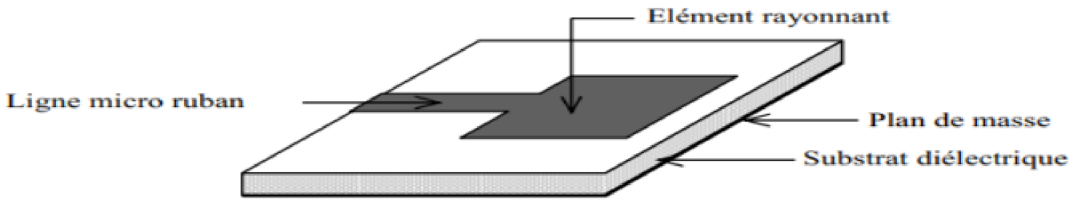


Figure 3 : Microstrip Line Feed [10]

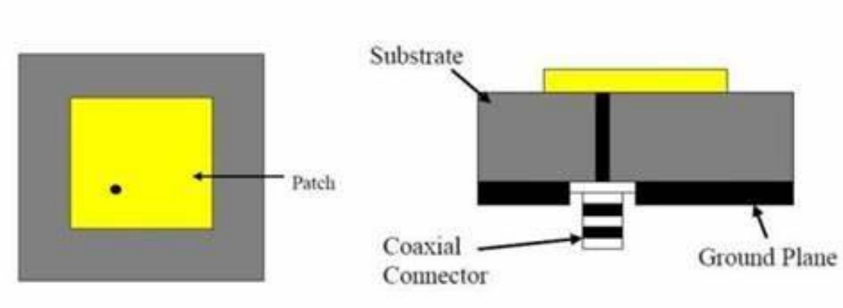


Figure 5: Top and side view of coaxial feed [13]

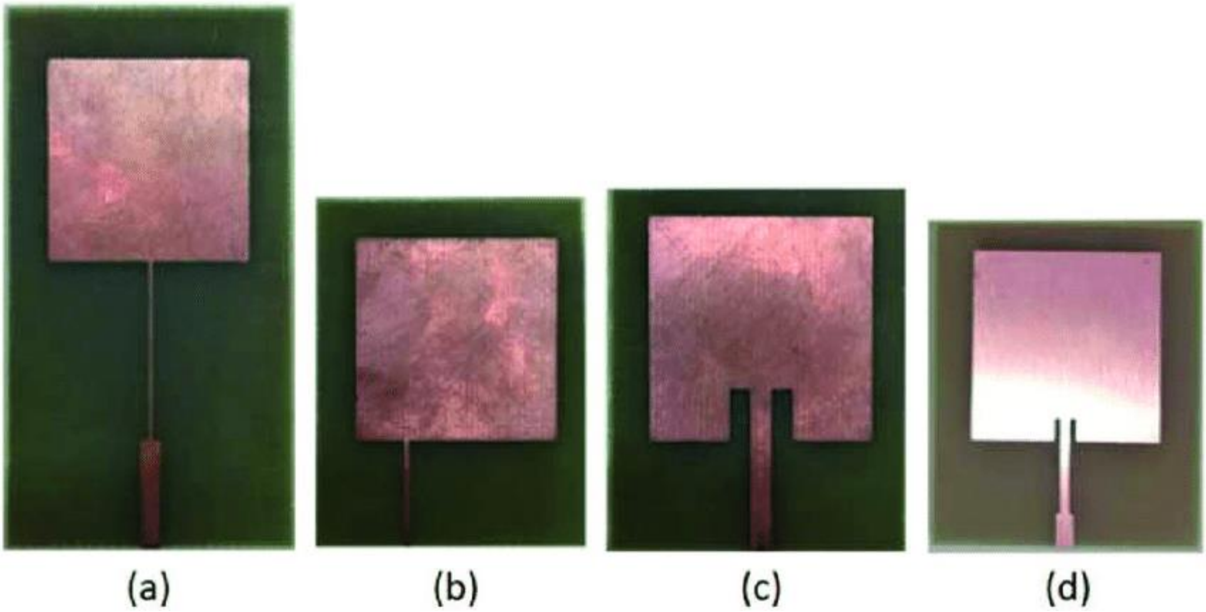


Figure 4: Microstrip line feed techniques [11]

1.5.2 - Coaxial probe feed

The coaxial feed shown in Figure 9. Also called probe feed is broadly used technique for feeding microstrip patch antennas. In this technique, the inner conductor of the coaxial connector is drawn through the dielectric and soldered on the radiating patch, while the outer conductor is attached to the ground plane. [12]

Unlike other techniques, the coaxial probe feed has the flexibility of insertion the feed so as to get perfect input impedance matching which may help to avoid return loss. Also provides an easy approach for the fabrication. [13]

However, this method has disadvantages in terms of the radiation diagram. In fact, the connection generates a current peak localized at the level of the radiating element that can induce a dissymmetry in the radiation diagram. In addition, losses occur with drilling the mass plane, the dielectric as well as the plated element. [14]

1.5.3 - Proximity-Coupled Microstrip-Line Feed

A configuration of this non-contacting microstrip feed used two-layer substrate with the microstrip line on the lower layer and the patch antenna on the upper layer. This feeding method contains two dielectric layers i.e., one is a radiating patch layer and on lower layer feed line is fabricated with a ground plane on back side. The two substrates are separated by a common ground plane. The microstrip feed line on the lower substrate is electromagnetically coupled to the patch through a slot aperture in the common ground plane. The slot can be of any shape or size and these parameters can be used to improve the bandwidth. The radiation from the open end of the feed line does not interfere with the radiation pattern of the patch because of the shielding effect of the ground plane. This technique has the provision of choosing separate substrate for the patch and the feed line in order to achieve an optimize performances. The major drawback of this method is difficulty in fabrication due to multiple layers which need proper alignment. Also, in this method the thickness of the antenna increases. The open-ended microstrip line can also be used to feed a patch antenna through proximity coupling, as shown in Figure 10. Proximity-fed microstrip antennas can leverage an open-ended microstrip line for impedance matching. Placed strategically under the patch at its near-100 ohm point, this line's inductive reactance cancels the patch's capacitance, achieving a matched impedance (around 50 ohms) for better signal transfer and reduced losses.
[1].

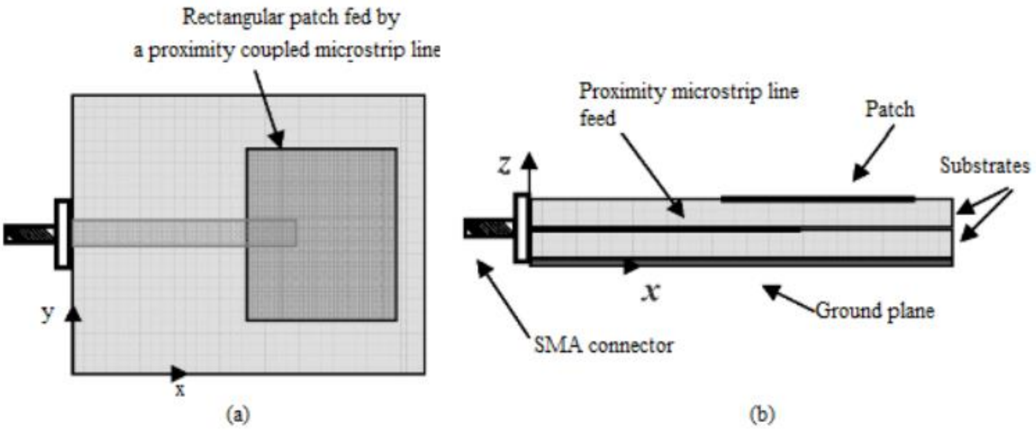


Figure 6: Proximity coupled feed (a) top view and (b) side view [1]

An open-ended microstrip line could be placed parallel to the edge of a patch to induce excitation via fringe-field coupling as shown in Figure 6. Both methods prevent soldering, which can improve mechanical reliability.

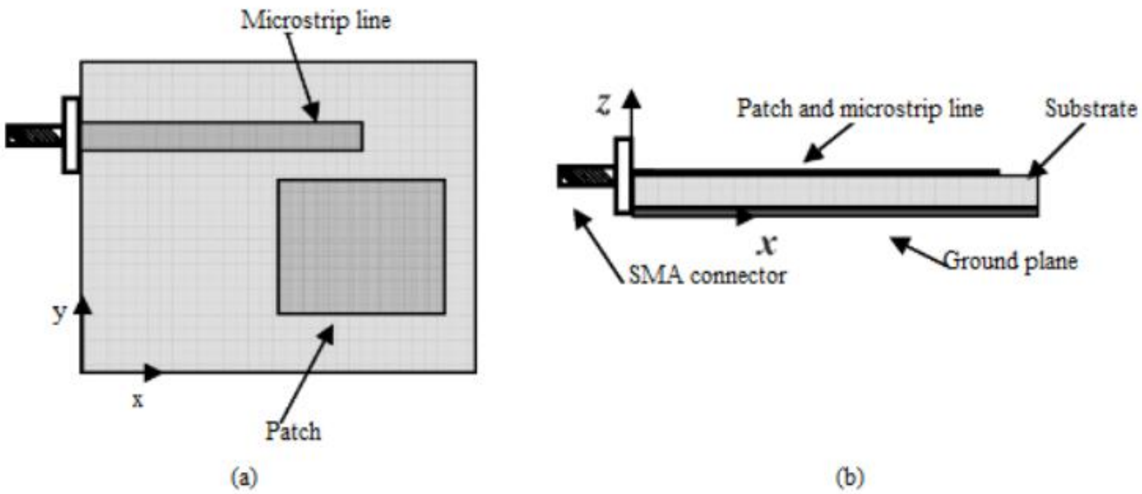
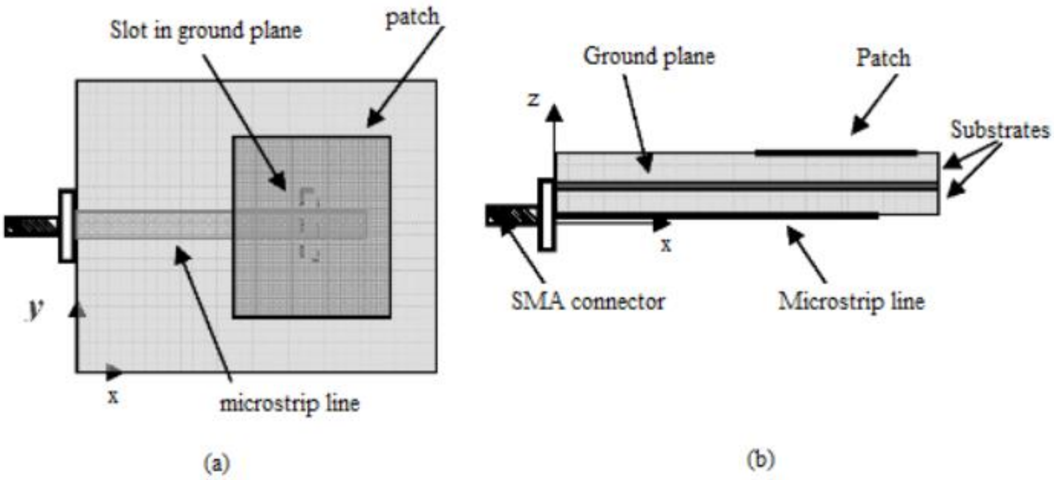


Figure 7: The geometry of a patch antenna fed by an adjacent microstrip line (a) top view and side view (b) [1]

1.5.4 - Aperture-Coupled Feed

The aperture-coupled technique was first introduced by D.M.Pozar in 1985 [15].It is composed up of two substrates with a common conductive ground plane in the middle. The patch is located on top of the substrate, whereas the feedline is located on the bottom substrate. The conductive ground plane between the feed and the patch antenna causes electromagnetic radiation to be "directed" to the patch through the slot without any physical connection, as shown in Figure 12. In fact, this technology is utilized to avoid both soldering connections and line leakage radiation that interferes with patch radiation. Furthermore, by employing a thick substrate, this feed method allows the patch to have a broader bandwidth than the coax probe feed.



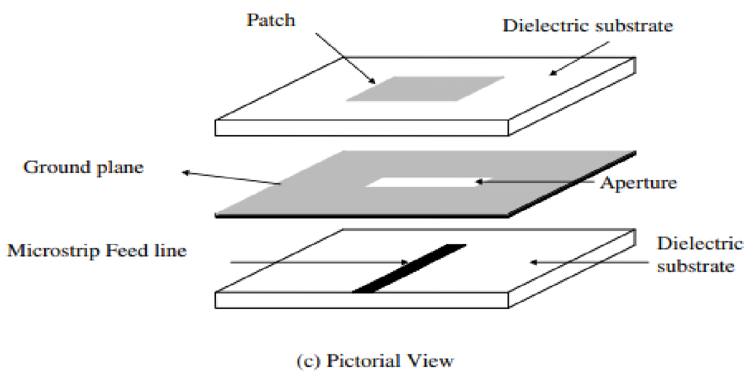


Figure 8 :a) top view b),c)side view of Aperture coupled feed [1]

1.5.5- Comparison between these different feeding technique

Feature	Microstrip Feed	Coaxial Feed	Proximity Coupled Feed	Aperture Coupled Feed
Feed Parasitic Radiation	Highest	Highest	Lowest	Minimum
Reliability	Best	Poor due to soldering	Good	Good
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth (achievable with 2-5% impedance matching)	2-5%	2-5%	2-5%	13%

Table 1: Comparison between feeding techniques

1.6- Antenna characteristics

Antenna characteristics are divided into two categories: electrical characteristics (input impedance, reflection coefficient, and bandwidth) and radiation characteristics (antenna radiation diagram, gain, directivity, and polarization).

1.6.1 - Input impedance

An antenna input impedance is the impedance seen at the input of this component. It is represented by: Ze(f) = Re(F) + j Xe(f). The input resistance Re(f) represents a dissipation term. It is related, on the one hand to the power radiated and on the other, the power lost by the Joule effect. The latter is generally small relative to the power radiated to ensure the optimal operation of the antenna. However, Joule-effect losses may represent not negligible values depending on the antenna geometry.

Losses in the mass plan are also to be taken into account. Reactance Xe(f) is related to the stored and concentrated reactive power near the antenna [16] [17].

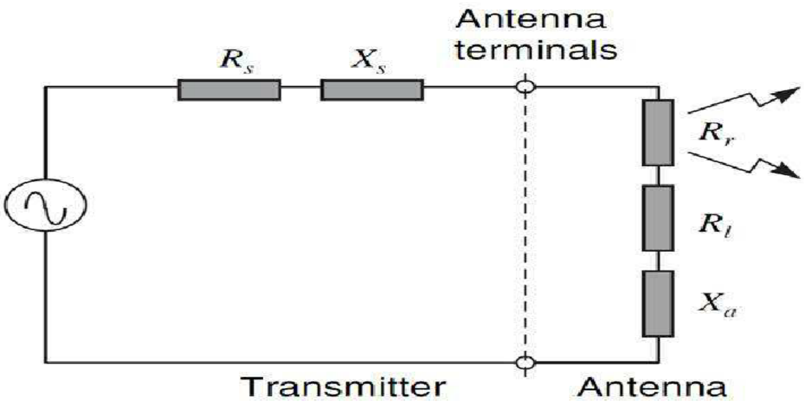


Figure 9:Equivalent circuit of an antenna [75]

1.6.2 - S parameters

Scattering parameters, also known as S-parameters, are a crucial set of measurements used to characterize the electrical behavior of antennas, particularly when analyzed using the

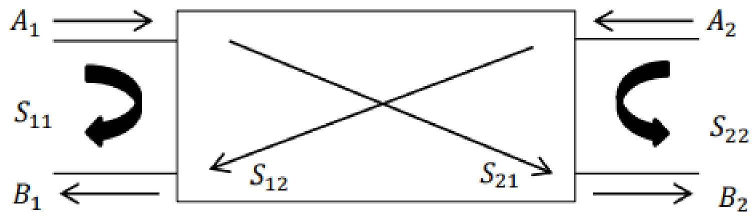


Figure 10: Representation in quadripole [70]

quadripole model. This model simplifies the analysis by representing the antenna as a four-port device with two input ports and two output ports as shown in fig 14.

Essential S-parameters for Antennas are:

1.6.2.1- S11 reflection coefficient

The maximum electromagnetic energy emitted by the source should reach the antenna to radiate into the open space. For this reason, guides must be carefully designed to prevent the electromagnetic waves being reflected by sudden discontinuities at the operating frequency of the antenna. If this is the case, the energy will be reflected to the source, destructive interference is likely to occur and so-called stationary waves are generated in the guided environment. This environment becomes a storage element of electromagnetic energy and no longer fulfils the role of its propagation map [18].

To measure the energy of these return sources, the reflection coefficient is calculated based on the frequency. The reflection coefficient is the ratio of reflected wave B1 to incidence (or return). Usually recorded as Γ or S11.

It is usually expressed in decibels (dB). Let us recall the link between the magnitude expressed in decibels and the Magnitude in natural magnitudes in the equation:

$$S11dB = 20 \times \log 10(|S11|)$$

We can therefore see that parameter S11 should be the smallest in the antenna design. antenna design. The reflection coefficient is an important parameter because it allows us to define other important concepts in the characteristics of the antenna. Thanks to reflection coefficient, it is possible to define the notion of matching and the frequency band (passband) where the antenna can be used. band (pass band) where the antenna has a reflection coefficient below a certain level (generally -10dB).

1.6.2.2- S12 Reverse Transmission Coefficient

Within this quadripole representation, S12 specifically refers to the reverse transmission coefficient. It quantifies the amount of energy that is transmitted from the output port (Port 2) of the antenna to the input port (Port 1). This transmission, also known as leakage, is typically unwanted and can lead to several issues.

$$S12dB = 20 \times log10(|S12|)$$

1.6.2.3- S21 Insertion Loss

In a quadripole representation, S21 specifically refers to the forward transmission coefficient also known as insertion loss. It quantifies the amount of power that is transferred from the input port (Port 1) to the output port (Port 2) of the antenna. This power transfer represents the desired signal that the antenna is intended to radiate.

$$S21dB = 20 \times log10(|S21|)$$

1.6.2.4- S22 Forward Reflection Coefficient

S22 specifically refers to the forward reflection coefficient. It quantifies the amount of power that is reflected back from the output port (Port 2) of the antenna towards the input port (Port 1). This reflection represents the signal power that is not effectively radiated by the antenna.

Figure 15 shown the all four parameters.

$$S22dB = 20 \times log10(|S22|)$$

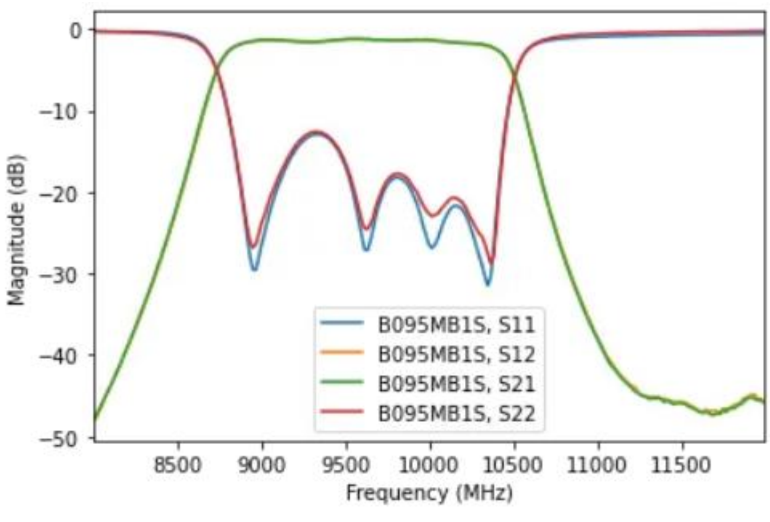


Figure 11: All Four S-Parameters in one plot [74]

1.6.3 - Bandwidth

The bandwidth of an antenna is defined as "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." The bandwidth can be considered to be the range of frequencies, on either ide of a center frequency (usually the resonance frequency for a dipole), where the antenna characteristics (such as input impedance, pattern, beamwidth, polarization, side lobe level, gain, beam direction, radiation efficiency) are within an acceptable value of those at the center frequency [9] ,figure 16 shown the bandwidth.

The bandwidth can be given as:

$$\mathbf{BW}(\%) = \frac{fh - fl}{fc} \times 100$$

Where:

fh: Upper frequency limit of the bandwidth.

fl: Lower frequency limit of the bandwidth.

fc: Center frequency of the antenna**.**

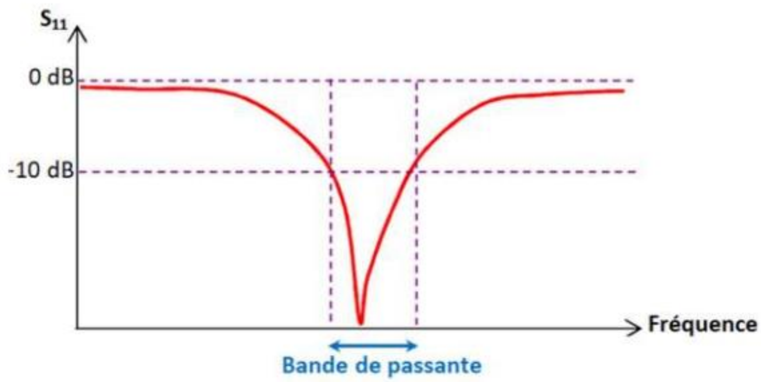


Figure 12: Definition of bandwidth [10]

The important terms in the context of an antenna's bandwidth are wideband and multiband.

a) **Wideband:** refers to the ability of antenna to transmit or receive signals over a wide range of frequencies, facilitating rapid data transmission over wide spectra from several hundred MHz to several GHz.
b) **Multiband:** refers to an antenna's ability to operate on several distinct frequency bands, enabling versatile connectivity and adaptability to varied communication standards and specific regulations.

1.6.4- Directivity

The directivity of an antenna characterizes the way that the antenna focuses its radiation in certain directions of space. [19]

Therefore, its defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions [9].

It may be expressed as:

$$D = \frac{U}{U0} = \frac{4\pi U}{P\text{rad}}$$

If the direction is not specified, it implies the direction of maximum radiation intensity

(maximum directivity) expressed as:

$$D = \frac{U\text{max}}{U0} = \frac{4\pi Umax}{P\text{rad}}$$

Where:

D = directivity (dimensionless)

D0 = maximum directivity (dimensionless)

U = radiation intensity (W/unit solid angle)

Umax = maximum radiation intensity (W/unit solid angle)

U0 = radiation intensity of isotropic source (W/unit solid angle**)**

Prad = total radiated power (W)

1.6.5 - Gain

Another useful measure describing the performance of an antenna is the gain. Although the gain of the antenna is closely related to the directivity, it is a measure that takes into account the efficiency of the antenna as well as its directional capabilities [9].

An antenna's gain is expressed as the ratio of intensity in a given direction to the radiation intensity if the power accepted by the antenna was radiated isotropically. The radiation intensity corresponds to the isotropically radiated power equals the power accepted by the antenna divided by 4π." In equation form, this can be showed as:

$$Gain = 4\pi \frac{radiation\ intensity}{total\ input\ (accepted)\ power} = 4\pi \frac{U\ (\theta\ ,\varphi)}{Pin}$$

1.6.6 - Polarization

The polarization of an antenna derives from the orientation of the electrical field emitted. It is defined by the type of wave polarization, it transmits in a given direction (usually in the main axis), and in the distant area [20].

Harmonic fields can be classified into three types of polarization based on trace shape: linear, circular, and elliptical as shown in figure 17.

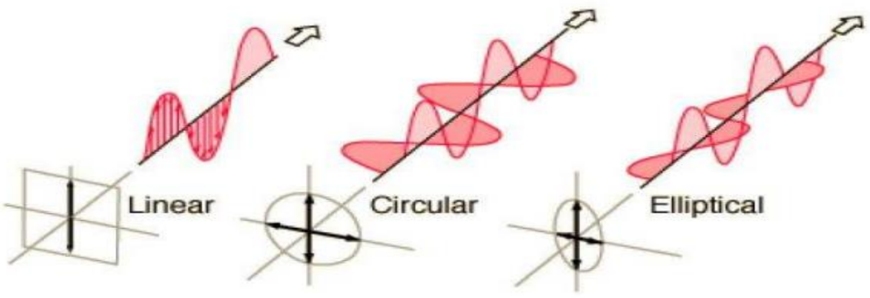


Figure 13: The different types of polarization [10]

1.6.7 - Radiation pattern

The radiation diagram is defined as a mathematical function or a graphical representation of the radiation properties of the antenna based on spatial coordinates as shown in figure 18. In most cases, the radiation profile is determined in the region of the distant field and is represented by directional coordinates. Radiation properties include the density of the power flow, the intensity of radiation, field intensity, directivity, phase or polarization. The most worrying property of radiation is the two-dimensional spatial distribution of the radiated energy depending on the observer's position. This can be represented in different forms:

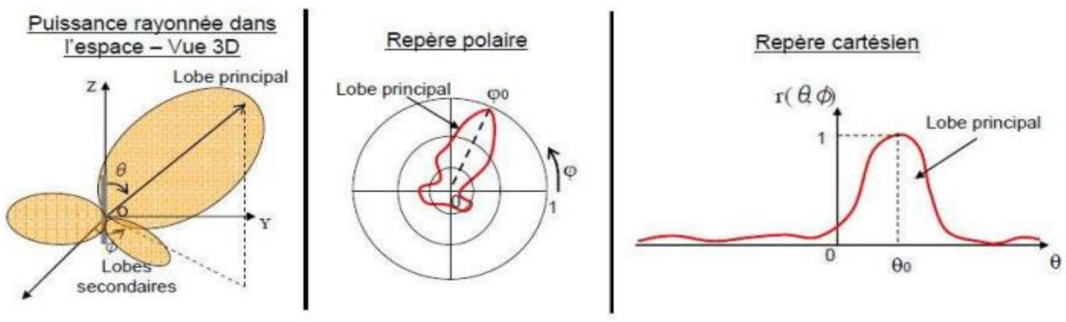


Figure 14:The different shapes of the radiation diagram [10]

1.7- Dual polarized multiband antenna

According to the advantages of the microstrip antennas mentioned above these latter can be multiband and multiple polarization. For this we approach the techniques used to obtain the multiband antennas and dual polarized antennas.

1.7.1 - Techniques employed to achieve multiband antennas

The methods used to make an antenna resonate at several frequencies are very diverse and established on multiple concepts are the following:

1.7.1.1 - Combination of multiple radiating elements

The most classical method to obtain multi-band antennas is the combination of two or more single-band radiating elements (resonators) as shown in figure 19. These single-band elements can be of the same type [21] [22]or different from each other. The elements constituting these multi-band antennas can be fed in two different ways:

▪ Direct feed by excitation port: In this state, these points are referred to as active or driven points.

▪ Feed by electromagnetic coupling with a nearby excited point fed directly: In this position, these points are referred to as parasitic or passive points.

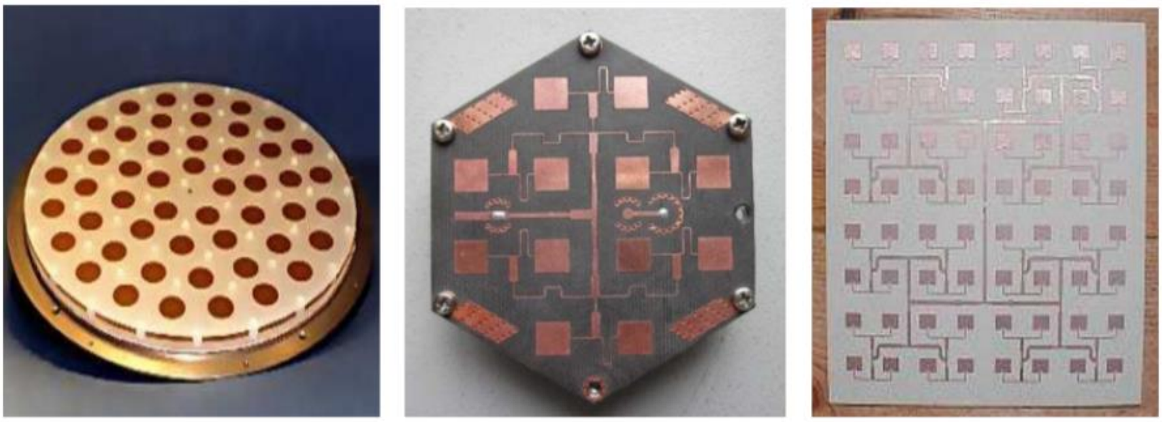


Figure 15:Antenna network for multi-band operation [23]

The various radiating elements of these antennas generate their own resonant frequencies and beyond. If a high bandwidth is desired, the resonant lengths of these resonant lengths of these elements of the same order of magnitude [24]. If you wish to have distinct frequency bands, it is necessary to cut each resonator in a different way each resonator [25]. By adding up the two previous principles, it is therefore conceivable to multi-band antennas.

When it comes to printed antennas, there are two possible ways that many rayonnant elements can be associated: either they are arranged in a single plan [26] or they are stacked one on top of the other. It is also possible to combine the two approaches, although at the expense of a significant increase in the Antenna's global volume [19] as shown in figure 20.

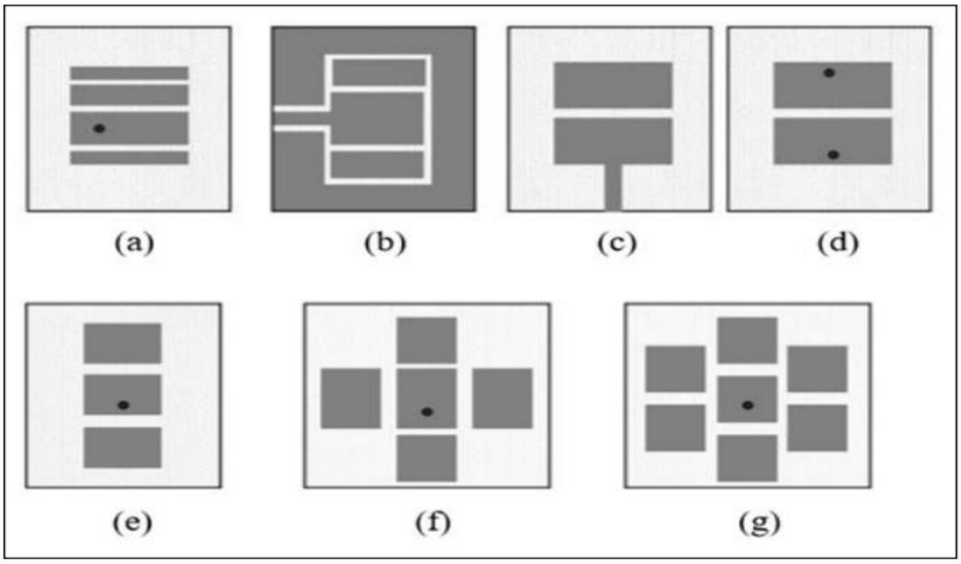


Figure 16:Coplanar arrangement of patches [23]

Strengths points	Weaknesses points
- Easy first dimensioning of the components - Relatively identical radiation throughout the covered broadband - Good efficiency	- Generally cumbersome structures - Coupling between elements not always mastered. - Good positioning of the different radiant elements delicate. - Radiation diagrams usually disturbed by other radiating elements. - Number of excitation ports in the case of separate excitations.

Table 2 : Strengths and weaknesses of the combination of multiple radiant elements

1.7.1.2 - Fractal technique

These are very special antennas that can achieve multi-band operation using fractal shapes. Fractals are an effective solution for increasing the perimeter of the surface. Obviously, the circumference of the antenna is a key factor in determining the resonant frequency. A fractal antenna with a given perimeter covering a smaller area than a similar square antenna. Figure 21 shows some types of fractal antenna. [27]

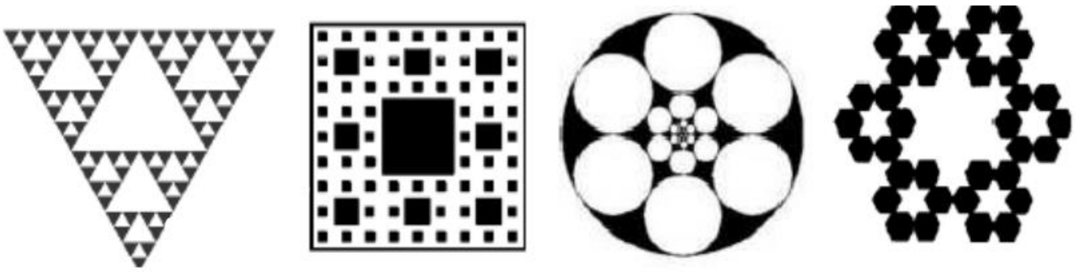


Figure 17: Different kinds of fractal antennas [27]

Strengths points	Weaknesses points
• Very small occupied surface: the compactness is the result of the irregular nature of fractal shapes. • Multiple resonances: the multi-band character comes from the character of self-similarity. • Very significant gain in some cases.	• Low gain in other cases. • Very difficult realization related to the complexity of the shapes. • Lower bandwidth than spiral antennas. • Difficulty controlling polarization.

Table 3 : Strengths and weaknesses of fractal technique

1.7.1.3 - Slot technique

In recent years, the increase in the number of communications standards (GSM 900, DCS 1800, UMTS, WLAN, BLUETOOTH, etc.) has led researchers to come up with increasingly complex antenna designs, generally using short-circuited structures or radiating slots to lower the higher modes [28]. Figure 22 shows some forms of slotted antenna.

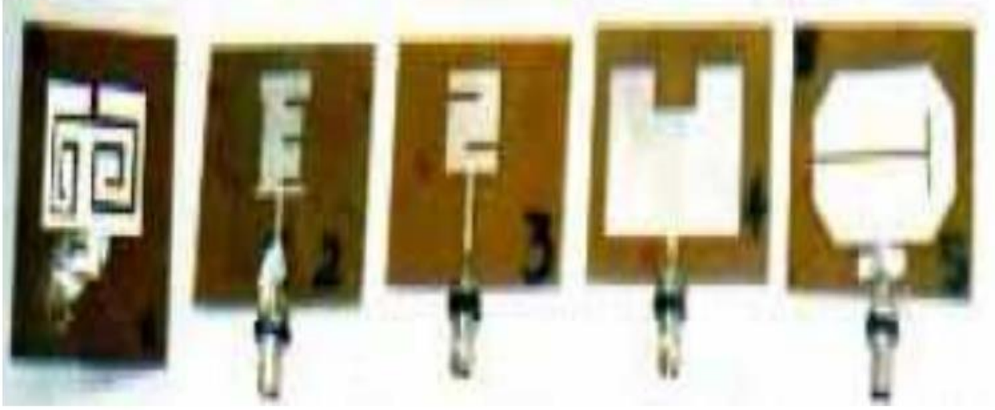


Figure 18: Slot antenna for multi-band operation [27]

1.7.2- Techniques employed to achieve dual polarization

Dual-polarized antennas in modern communication systems have used for combating multipath and fading effects. These antennas should have high isolation and low cross polarization within their impedance bandwidth. Dual polarized microstrip patch antennas could provide these features with low cost and easy fabrication [29].

A dual-polarity antenna is an antenna that is capable of receiving and transmitting radiofrequency signals with two distinct forms of polarization (usually horizontal or vertical polarization), simultaneously.

There are several techniques that can be employed to achieve dual polarization in antennas

1.7.2.1.Two orthogonal microstrip patch antennas

Two orthogonal microstrip patch antennas are a popular design for achieving dual polarization in antenna systems. This configuration involves placing two microstrip patch antennas on the same substrate, oriented at 90 degrees to each other. One patch is aligned horizontally, while the other is aligned vertically, enabling the antennas to transmit and receive signals in two orthogonal polarization planes. Each patch antenna is fed independently with its own microstrip feed line, ensuring that the horizontal patch excites horizontal polarization and the vertical patch excites vertical polarization

1.7.2.2. Slot coupled

A classical way to obtain a dual-polarized slot-coupled microstrip antenna consists in cutting two offset orthogonal slots in the feed-line ground plane. Each slot excites the patch in a distinct direction (typically horizontal or vertical). [30]

This technique offers a relatively simple design but may have limitations in achieving high isolation between the two polarizations, a crucial factor for some applications.

For improved isolation, alternative slot shapes can be explored. Some options include:

- **Cross-shaped slots:** These offer potentially better isolation compared to offset slots, but often necessitate a more complex feed arrangement or a multilayer antenna structure to minimize unwanted coupling between the feed lines exciting each slot [31].

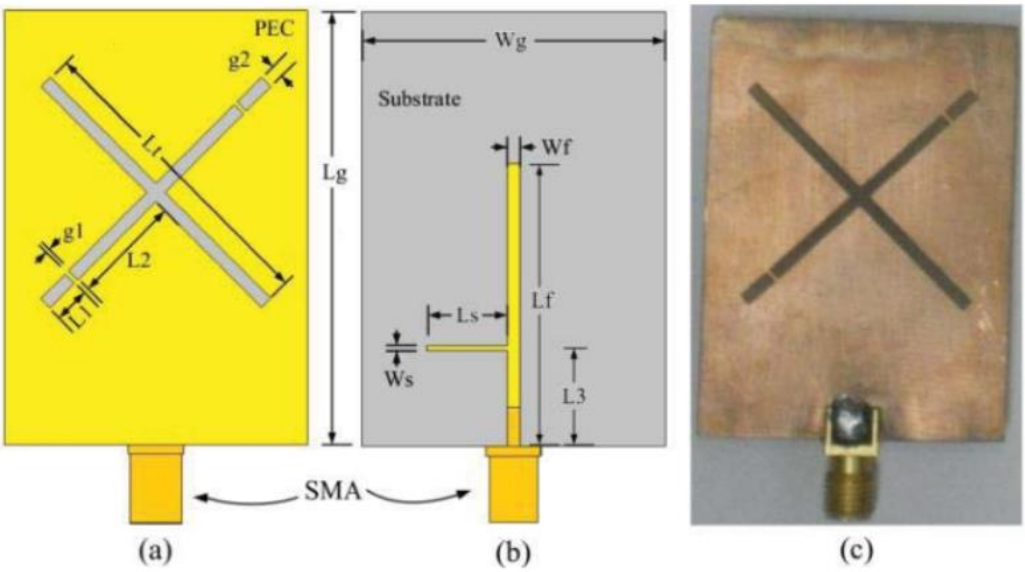


Figure 19:Example on cross shaped technical slot (a) top view (b) bottom view (c) fabricated prototype [32]

- **H-shaped slots:** These can achieve good isolation but may require careful design optimization for optimal performance [33] .

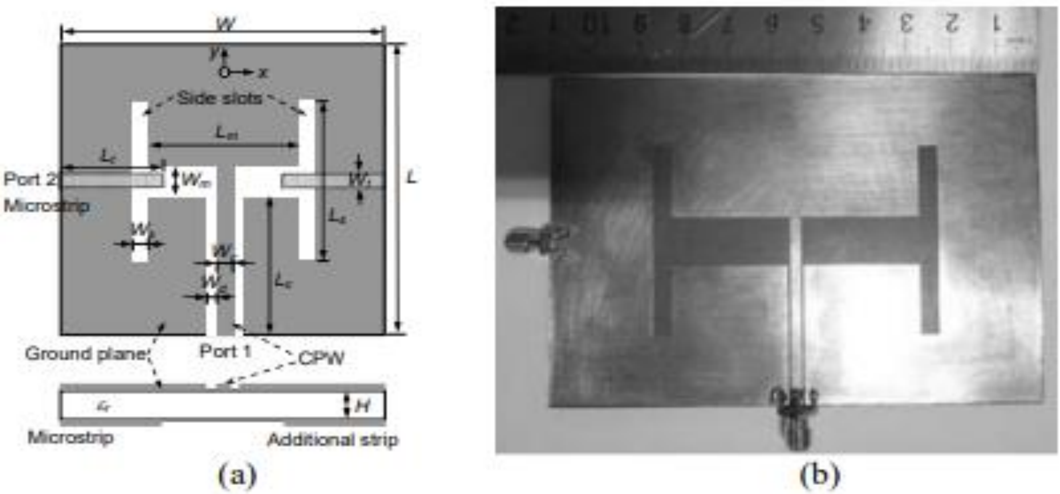


Figure 20 : Example on dual-polarized H-shaped slot antenna with top and side view and (b) photograph of an antenna prototype in top view [34]

1.7.2.3.- Aperture Coupling

Another technique for obtaining a dual-polarized aperture-coupled microstrip antenna as shown in figure 25 involves cutting two offset orthogonal apertures in the feed-line ground plane, with each aperture exciting the patch in a single direction. Investigations of patches excited in this manner have revealed that the isolation between the two input ports is 18 dB. [35].

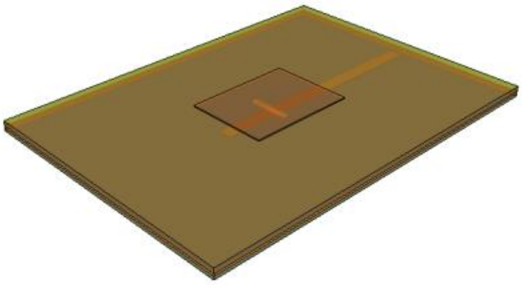


Figure 21 Aperture Coupled Microstrip Patch Antenna [36]

1.7.2.4.- Two port feed network

This technique will excite two independent dominant mode from the patch with fed at the dual central point. Thus, the patches mode will degenerate at the far fields and produce the orthogonal and linear polarized at angles of designed [37]. A patch with corner fed also can excite two orthogonal polarized with equal amplitude and in phase. The corner fed method produce higher isolation as compared to edge center fed method [38] [39].Figure 26 shown this technique.

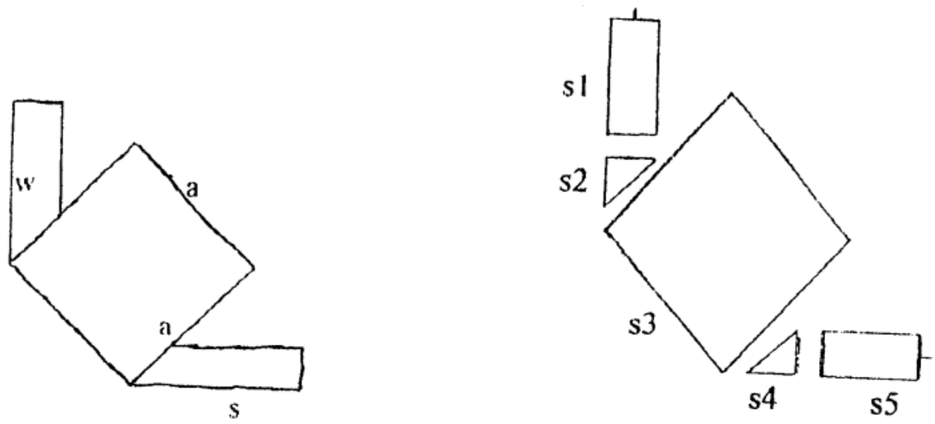


Figure 22 :Two port feed dual polarized antenna [38]

1.7.2.5. - Two feed probes

Dual linear polarized antenna can also develop by using square patch with two feed probes. Each feed probe will generate one polarized signal primarily such as horizontally and vertically polarization [40],Figure 27 shown the prob fed technique.

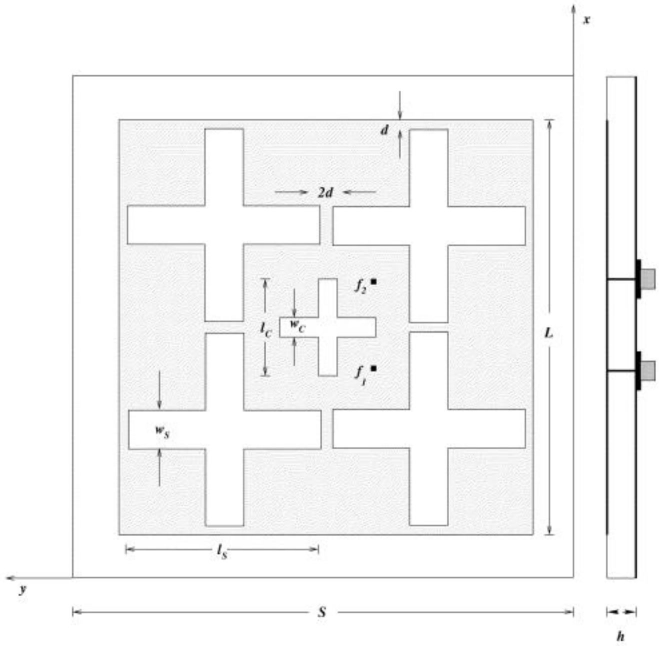


Figure 23 : Prob-fed dual polarized microstrip antenna [41]

1.8- State of the art of dual polarized multiband antennas

In [42] ,researchers have proposed a new design for a microstrip antenna (MSA) that uses a crescent shape to achieve multiple bands and dual polarization. This design modifies a regular circular patch antenna to create new resonant modes close to those of a circular patch in TM11 and TM21 modes. This results in an antenna with four operational frequency bands while maintaining dual polarization. Each band offers a bandwidth of 1 to 1.5% and exhibits a broadside radiation pattern. The researchers have also developed an equation to predict the resonant frequencies based on the dimensions of the crescent shape. This equation closely matches the results obtained through simulations. Additionally, they presented a design where the crescent-shaped patch is suspended in air, achieving a co-polar peak gain of over 1.5 dB, figure 1 presents this technique.

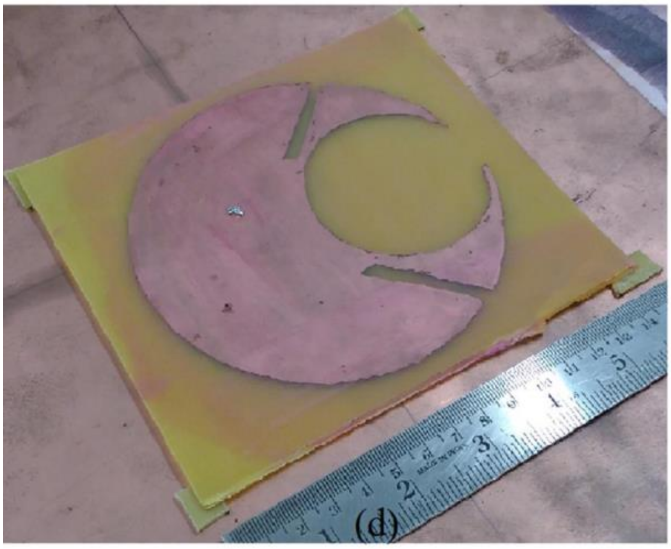


Figure 24:Slot cut crescent shape [42]

In [43] ,this research delves into the design of multi-band, dual-polarized microstrip antennas. Traditionally, such antennas incorporate stubs or slots, requiring precise placement to manipulate the patch's resonant modes (frequencies where it efficiently vibrates) and impedance (resistance to electrical current). This researh focuses on a variation: a slot cut into a circular microstrip patch. The study explores how this slot alters the patch's initial resonant modes. These modified modes are then "degenerated" into two distinct, orthogonal modes, allowing the antenna to operate at multiple frequencies while maintaining dual polarization (transmitting and receiving signals in two perpendicular directions). The research presents equations for calculating the resonant lengths of the modified patch and demonstrates their accuracy through close agreement with simulated frequencies. Finally, to improve signal strength (gain), an air-suspended design for the slot-cut antenna is introduced, achieving a broadside gain (gain in the desired direction) of 1.5 to 6 dB across the multiple operational frequencies.

In [44],authors examine low-profile triband dual-polarized dipole antenna designed for base-station applications, featuring a stable radiation pattern, consistent gain, and adjustable bandwidths. The antenna employs two crossed dipoles, fed by microstrip-to-slot line baluns, to provide stable radiation with ±45° polarization across a wide frequency range of 2.3–5.5 GHz. An octagonal ring and triangular stubs create two notched bands at approximately 2.8 GHz and 4.2 GHz, segmenting the broad frequency range into three distinct bands. The triple bandwidths can be adjusted by tuning the position and total length of the parasitic ring and stubs. The antenna achieves three operating bands: 2.25–2.72 GHz, 3.24–4 GHz, and 4.57–5.16 GHz. It maintains a stable half-power beamwidth of 65.2° ± 4.3° in the lower band, 72.2° ± 6.4° in the center band, and 66.5° ± 3.8° in the higher band. Additionally, the gains are consistent across the bands, with values of 8.5 ± 0.5 dB, 8.4 ± 0.4 dB, and 8.2 ± 0.6 dB, respectively. These outstanding performance characteristics make this design highly suitable for practical applications.

In [45] ,a new microstrip antenna design overcomes limitations of antennas in multi-band communication is presented. This versatile antenna operates in both bands and boasts dual-linear polarization for flexibility in signal handling. The key improvement lies in its enhanced performance compared to older designs. It achieves wider bandwidth (at least 3.65% for S-band) and minimizes unwanted signal leakage (high isolation: 26 dB for S-band and 45 dB+ for C-band). This improved performance is due to innovative coupling techniques: proximity coupling for S-band and aperture coupling for C-band. These techniques ensure efficient power transfer between the feeding lines and the radiating patches. Overall, this groundbreaking design offers significantly improved bandwidth and isolation for S-band and C-band communication, paving the way for more efficient and reliable wireless technologies. Figure 2 shown this technique.

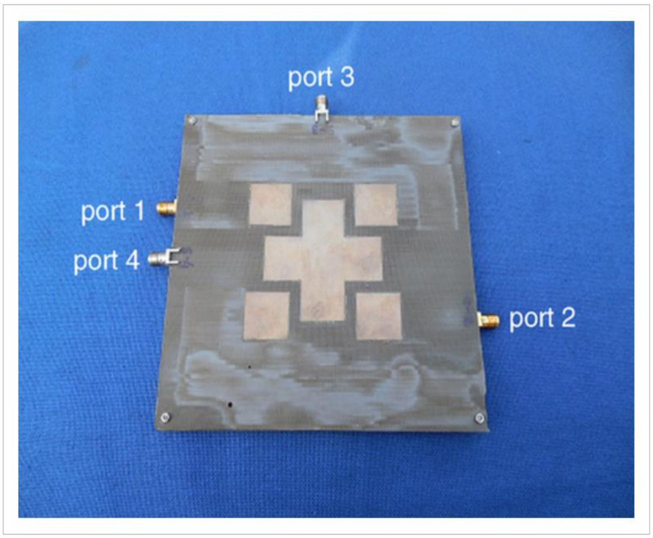


Figure 25: Inter-port isolation microstrip antenna [45]

In [46] author presents a novel antenna design characterized by an ultra-thin profile, achieving just 0.32 times the operating signal wavelength. This significant size reduction caters to applications with stringent spatial constraints, enabling functionality in space-limited environments where conventional antenna designs may prove impractical. But its benefits go beyond its compact size. The design boasts dual-band operation, meaning it can work efficiently in two separate frequency ranges.

Additionally, it offers dual-polarization, allowing for signal transmission and reception in both horizontal and vertical directions for each band.

In conclusion, this research presents a groundbreaking antenna design as shown in figure 3 that is not only compact but also offers dual-band operation, dual-polarization, and built-in filtering capabilities. This combination of features makes it a promising candidate for future wireless communication systems, particularly those with demanding requirements for efficient signal processing and transmission.

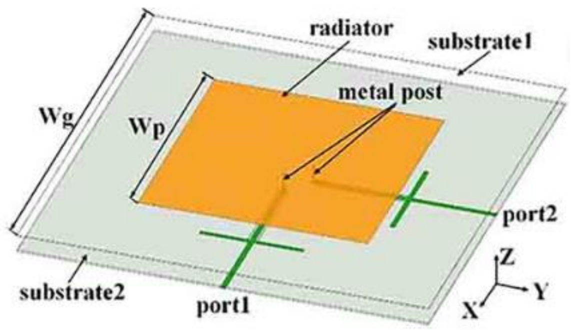


Figure 26: A low profile, dual-band dual-polarized patch antenna [46]

Researchers in [47] have developed an innovative antenna design specifically for many devices used in Wireless Body Area Networks (WBANs) as shown in figure 4. This new antenna operates in two distinct frequency bands: 2.45 GHz and 5.8 GHz. It also boasts dual-polarization, meaning it can transmit and receive signals in two different directions for each band.

The design cleverly utilizes different operational modes for each band depending on its placement on the body. At 2.45 GHz (typically for off-body communication where the antenna isn't directly touching the body), the antenna uses a mode that radiates outwards (broadside radiation). In contrast, for on-body communication at 5.8 GHz (where the antenna is worn on the body), the design switches to a mode that emits signals primarily along the axis of the antenna, similar to a monopole antenna.

This dual functionality is achieved through a simple yet effective design: a circular patch antenna with eight strategically placed slots. The antenna is fabricated using comfortable textile material, making it flexible and wearable.

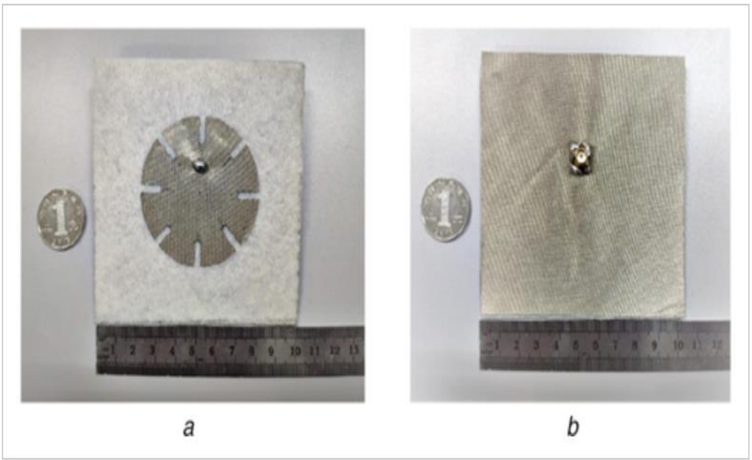


Figure 27: Circular patch for on/off body WBAN application [47]

1.8.1- Comparison between state of art references

Features	[42]	[43]	[44]	[45]	[46]	[47]
Type	Triband dipole	Multi-band crescent microstrip	Multi-band slot cut circular microstrip	Dual-band dual-polarized microstrip antenna	Dual-band dual-polarized patch antenna	Dual-band dual-polarized antenna
Frequency bands	2.25-2.72 GHz, 3.24-4 GHz, 4.57-5.16 GHz	Resonant modes near TM11 & TM21 of circular patch (frequency not explicitly mentioned)	Not specified	* S-band (generally 2 GHz - 4 GHz) * C-band (generally 4 GHz - 8 GHz)	Not specified	* 2.45 GHz (Industrial, Scientific, and Medical band) * 5.8 GHz (likely ISM band
Gain	Stable across bands: 8.5 ± 0.5 dB, 8.4 ± 0.4 dB, 8.2 ± 0.6 dB	Above 1.5 dB	1.5 to 6 dB	Between 6.5dB,12.3dB,12.5dB	8-8.8dBi	Off-body from 6.33 to 5.86 dBi at 2.45 GHz,on-body from 6.98 to 6.94 dBi

Table 4 : Evaluation of dual polarized microstrip antennas across different studies

1.9- Conclusion

In conclusion, microstrips and their geometry offer significant advantages, such as compact size and easy integration, particularly crucial in 5G base stations. Techniques for achieving dual-polarization and multiband microstrips herald new possibilities in wireless communications. Moreover, the potential integration of metamaterial-based reflectors like AMC holds great promise for enhancing the performance of microstrip antennas, thereby facilitating significant progress across multiple domains, including 5G.

Chapter 2

Wireless Networks, 5G, and Multi-Antenna Systems

Chapter 2: Wireless Networks, 5G, and Multi-Antenna Systems

2.1. Introduction

Wireless networks can be viewed as a computer network that uses wireless data connections between network nodes. It is a method by which homes, telecommunications networks and businesses avoid the costly process of installing cables into buildings for connections between various equipment [1].

In this chapter, we explore modern wireless networks and their evolution. We start by defining the different types of networks and the progression to 5G. The chapter also examines the essential components of the wireless communication chain, including the propagation channel, and performs a link budget analysis. We highlight advanced techniques such as MIMO (Multiple Input Multiple Output) and diversity, which enhance transmission reliability. Finally, we address the techniques for reducing mutual coupling between antennas in multi-antenna systems, crucial for optimizing performance in complex wireless environments.

2.2. Wireless networks

Wireless telecommunications involve several types of networks, classified according to their type of application and range as shown in figure 28.

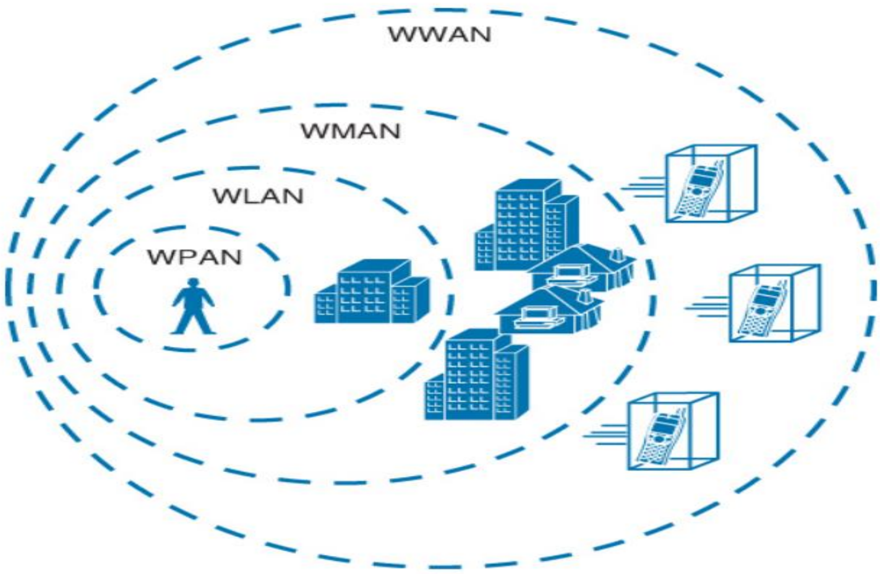


Figure 28: Wireless network types and scopes [48]

The main categories are as follow:

- **Wireless Personal Area Network (WPAN)**: Also known as a home network, it typically covers a few meters and allows data exchange between a modern device (smartphone, tablet) and an adapted network [49].
- **Wireless Local Area Network (WLAN):** WLANS allow users in a local area, such as a university campus or library, to form a network or gain access to the internet. A temporary network can be formed by a small number of users without the need of an access point; given that they do not need access to network resources. It implements a flexible data communication system frequently augmenting rather than replacing a wired LAN within a building or campus. WLANs use radio frequency to transmit and receive data over the air, minimizing the need for wired connections. A wireless local area network (WLAN) is a wireless distribution method for two or more devices that use high-frequency radio waves and often include an access point to the Internet. A WLAN allows users to move around the coverage area, often a home or small office, while maintaining a network connection [50].
- **Wireless Metropolitan Area Network (WMAN):** covers a larger area than that of a LAN and smaller area as compared to WAN. It connects two or more computers that are apart but reside in the same or different cities. It covers a large geographical area and may serve as an ISP (Internet Service Provider). MAN is designed for customers who need high-speed connectivity [51].
- **Wireless Wide Area Networks (WWAN**): Cellular technology is used in wireless WANs when the range of a wireless LAN or metropolitan network is not enough. Users can use these networks for phone calls to those connected to them via a wireless WAN or a wired telephone connection. Furthermore, they can also access web pages or server-based apps by connecting to the internet [52].

2.3. 5G evolution

The rapid growth of technology has resulted in a swift and significant evolution of WWAN. The evolution of WWAN has occurred in several distinct phases which are:

- **First Generation 1G:** in early 1980‘s, the first generation of WWAN was introduced, known as 1G. it use data transmission over Analog signals based on a technique called FDMA (Frequency Division Multiple Access) [53].

- **Second Generation 2G:** The 2nd generation was accomplished in later 1990‘s. The 2G mobile communication system is a digital system; this system is still mostly used in different parts of the world. This generation mainly used for voice communication also offered additional services such as SMS. In this generation two digital modulation schemes are used; one is time division multiple access (TDMA) and the 2nd is code division multiple access (CDMA) [54].
- **Third Generation 3G:** The turn of the century marked the launch of 3G, which brought significant improvements to WWAN technology. It introduced higher data transfer speeds, making it possible to stream media and browse the internet at faster rates. Additionally, 3G networks also allowed for simultaneous voice and data usage.
- **Fourth Generation 4G:** After its launch in 2013, the 3G network became reliable over the following decade. Almost all mobile devices are registered to use the 4G network, which operates in the 700 MHz, 1800 MHz and 2600 MHz frequency bands and offers better coverage and call quality. This has facilitated the development of a range of new services, including mobile payments and video conferencing [53]**.**
- **Fifth generation 5G**: it represents the latest evolution in Wireless Wide Area Network (WWAN) technology, offering significant advancements over previous generations. It is designed to meet the growing demands for high-speed, low-latency, and reliable mobile communication. Here are the key aspects of 5G technology for WWAN and its objectives, along with information about the frequency bands used [55].

5G is the first generation capable of operating in three different radio spectrums as shown in figure 29 :low, medium, and high band (also known as mmWave).

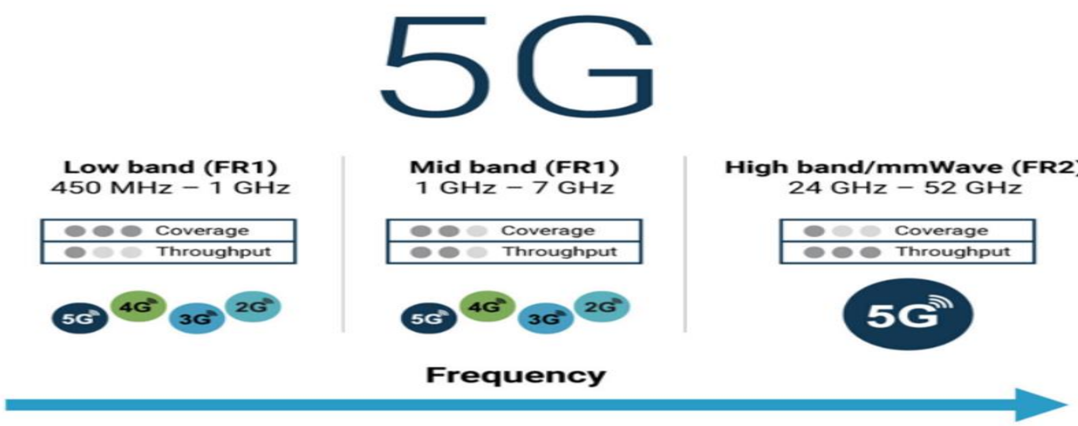


Figure 29 : 5G Spectrum [56]

- **Low bands**: Utilize the sub-1GHz, which covers a wider distance. It can pass through obstacles and is often used in low-density rural settings and public safety. 5G offers more comprehensive coverage than GSM 2G or 3G, as it has spectral efficiency over the previous technologies [57].
- **Mid band**: In many countries, the sub-6 GHz frequency band is a crucial spectrum range widely adopted for 5G deployment. This band is favored for its ability to provide extensive coverage, making it suitable for both urban and indoor environments due to its good range and penetration capabilities through obstacles like buildings and trees. The sub-6 GHz spectrum is divided into various frequency ranges, including low-band (600 MHz to 2.6 GHz) and mid-band (2.6 GHz to 7 GHz). Specific frequency bands utilized for 5G within the sub-6 GHz range include 600 MHz, 700 MHz, 800 MHz, 2.1 GHz, and 2.6 GHz, among others (Table5). Importantly, many of these bands also support LTE (Long-Term Evolution), enabling dual connectivity [58] strategies where 5G and LTE networks can be used simultaneously to enhance network performance and coverage.

Name of the band	Frequency Range (GHz)
n77	3.3 - 4.2
n78	3.3 – 3.8
n79	4.4 – 5.0
n257	26.5 – 29.5
n258	24.25 – 27.5
n260	37.0 – 40.0
n261	27.5 – 28.35

Table 5: 5G Opération Bands [58]

- **High-band** 5G is also known as millimeter-wave (mmWave) 5G. It operates on frequencies above 24GHz. These frequencies offer ultra-fast speeds, with the potential for speeds up to 10Gbps. However, high band 5G has a limited coverage area and is easily obstructed by obstacles such as buildings and trees.

The frequency band chosen for a 5G design will depend on the specific application, coverage requirements, and capacity needs. A combination of sub-6 GHz and mm Wave frequencies may be used for optimal performance in different use cases [59].

2.4. Communication chain

A fundamental component of wireless networks, the communication chain is responsible for ensuring the effective transfer of data between devices. It functions as an invisible bridge, linking transmitters and receivers via radio waves, and has a significant impact on the overall network performance, influencing factors such as reach, bandwidth, reliability, and communication security.Figure 30 shown the communication chain.

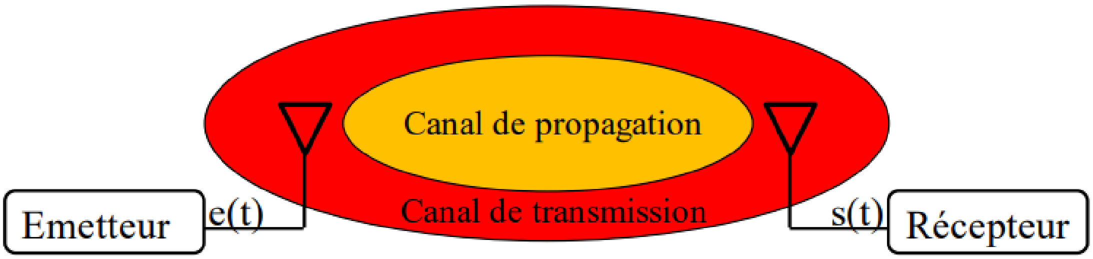


Figure 30: Synoptic schema of a communication chain [60]

2.4.1. Link Budget

The communication chain is susceptible to losses and degradations that can impair the quality of the signal received. In this context, the link budget is a fundamental instrument for evaluating communication performance and identifying potential avenues for enhancement.

The link budget is employed for the estimation of the signal level (or signal-to-noise ratio). This procedure allows designers to make informed decisions regarding the selection of appropriate elements, such as antenna gains and transmitted power, as well as the choice of transmission equipment and antennas to be utilized. This has implications for the financial aspects of the systems in question, as well as the licensing conditions that apply [61].

In wireless communications, one of the fundamental equations used to calculate the link budget is the Friis transmission equation. This equation relates the received power to the transmitted power, antenna-separation distance, and antenna gains in a free-space communication link. The equation is given by:

$$Pr = Pt\left(\frac{\lambda}{4\pi d}\right)^2 Gr\ Gt$$

Where:

- Pr : Received power
- Pt: Transmitted power
- Gt: Gain of the transmitting antenna

- Gr: Gain of the receiving antenna
- λ: Wavelength of the signal
- d: Distance between the transmitting and receiving antennas

The Friis equation is an essential tool for estimating the average signal attenuation in ideal free-space conditions. However, for practical applications, it is crucial to account for additional propagation phenomena that affect the signal, in order to design robust and reliable communication systems

2.4.2. Propagation channel

The propagation channel in wireless networks, specifically in the context of 5G, refers to the physical and environmental conditions that impact the transmission of electromagnetic waves between a transmitter (such as a base station) and a receiver (such as a smartphone). It encompasses all phenomena related to wave propagation. With the use of higher frequencies in 5G, such as sub-6 GHz and millimeter waves (mm Wave), the propagation channel becomes more complex due to increased susceptibility to obstacles and environmental factors.

For example, mm Wave frequencies used in 5G are highly affected by obstacles like buildings and trees, as well as atmospheric conditions such as rain and fog. Understanding these channel conditions is crucial for optimizing network performance, ensuring reliable communication, and achieving the high data rates and low latencies promised by 5G technology.

First of all, it is necessary to understand types of propagation and its phenomena that are characteristic of a given environment and that affect the transmission of radio waves.

2.4.3. Types of propagation

As previously stated, the propagation channel is the medium through which signals propagate in the form of multipath due to the obstacles surrounding the transmitter and receiver. The phenomenon of multipath propagation can be observed in two distinct propagation situations. In the context of wireless communication, NLOS (non-line-of-sight) refers to the absence of a direct line of sight between the transmitter and receiver. In this instance, the probability density of the fading amplitude of the total received signal follows Rayleigh's law, as illustrated in Figure 31. Furthermore, there is LOS (Line of Sight) direct visibility between the transmitter and receiver, as depicted in Figure 32. Consequently, the fading amplitude is characterized by Rice's distribution [62].

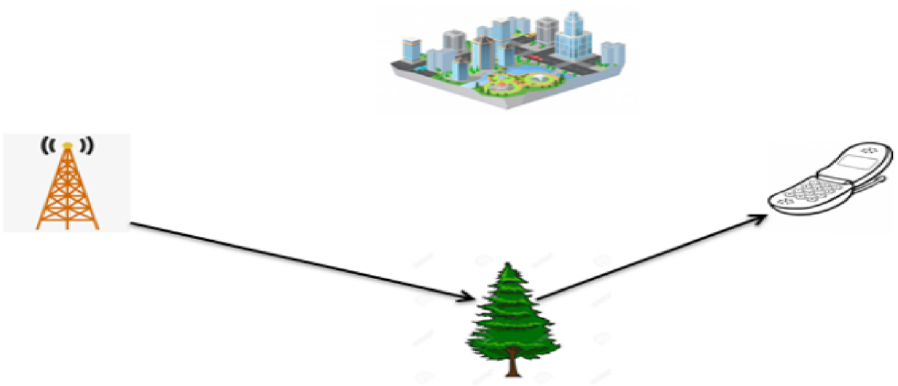


Figure 31: NLOS propagation [62]

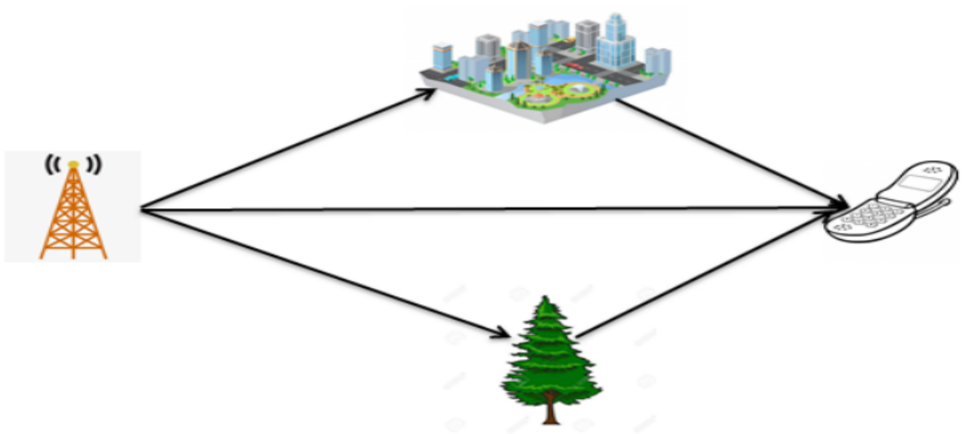


Figure 32: LOS propagation [62]

2.4.4. Physical phenomenon of radio propagation:

There are two types of radio phenomena: distortions of the electromagnetic wave and the superimposition of undesirable signals, known interchangeably as noise [63].

2.4.4.1 Radio noise

Noise refers to all signals that do not carry any useful information and interfere with the desired signal. It is a disturbance whose origins are the propagation channel (external noise) and the electronic devices used in the receiver (internal noise) [64].

2.4.4.2 Propagation model mechanisms

In the case of a physical wire, the wired channel is used as the medium, with the transmitted signal travelling directly from the transmitter to the receiver in a single path. However, when the medium is air or free space, the communication channel is referred to as the radio channel. In this instance, the signal radiates from the transmitter and spreads out in different directions, as illustrated in Fig. 33. A portion of the radiated wavefront directly reaches the receiver, constituting the direct signal. Additionally, other portions of the wavefront encounter reflecting surfaces (e.g., buildings, ground, and moving trains) and are reflected back to the receiver, forming the indirect ray. Consequently, in a wireless radio channel propagation environment, the receiver receives a multitude of reflected, diffracted, and scattered waves, in addition to the direct signal, shown in Figure 33.

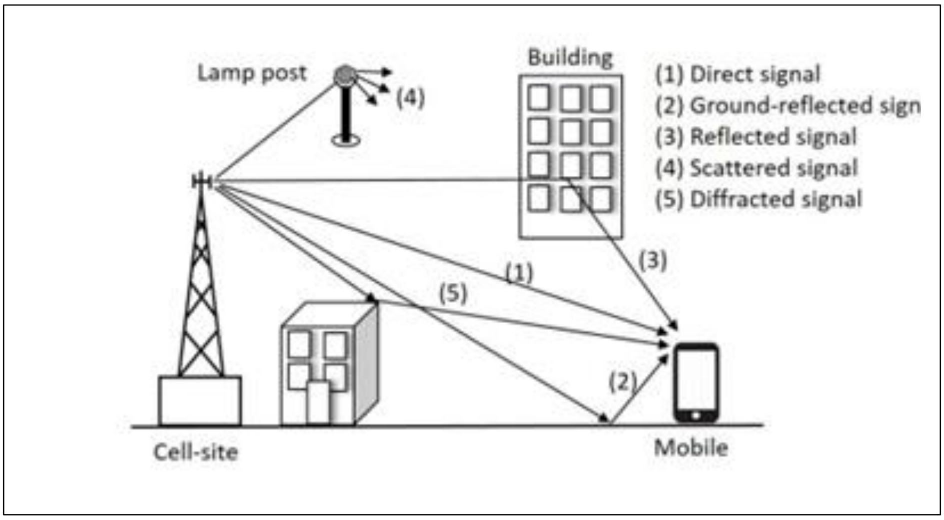


Figure 33 : Multipath propagation in outdoor scenario [65]

This section will describe the three basic propagation mechanisms [65]:

- **Reflection:** when a radio wave encounters a surface that is large relative to its wavelength, such as buildings, walls, or other large structures. The wave bounces off the surface and changes direction.
- **Diffraction:** where a wave encounters an obstacle or aperture, such as the edge of a building or a tree, and bends around the obstacle rather than being entirely blocked. This bending of waves allows signals to propagate around obstacles, enabling communication even when there is no direct line-of-sight path between the transmitter

and receiver. In essence, diffraction ensures that signals can reach their destination by bending around obstacles, thereby extending the coverage area and maintaining connectivity in scenarios where direct propagation is obstructed.

- **Scattering:** Scattering is a special case of reflection and it occurs when the radio wave propagates through a medium which consists of irregular objects (e.g., walls with rough surface, vehicles, foliage, lampposts, stairs, street sign, etc.) that is smaller compared to the wavelength.

The radio propagation mechanisms based on the above phenomenon and the medium can be affected by three parameters: permittivity ε, conductivity σ, and permeability μ. These parameters are called constructive parameters of medium.

2.5. Multi-antennas systems

Multi-antennas systems are increasingly used in wireless communications. With the advent of new standards, researchers have developed multi-antenna systems where each antenna operates in a different frequency band. This approach aims to avoid multipath phenomena that can cause signal fading, or to improve channel capacity. However, the physical proximity of antennas poses a cohabitation challenge that can potentially reduce their overall efficiency, especially in the case of multi-standard antennas. To overcome these challenges, techniques such as MIMO (Multiple Input Multiple Output) and diversity are employed. These techniques aim to optimize resource management, minimize interference and improve the reliability of wireless communications by dynamically adapting antenna configuration to propagation channel conditions [66].

2.5.1. MIMO (Multiple Input, Multiple Output)

MIMO techniques were introduced in the 1990s by Gerard J. Foschini to increase the speed and range of wireless networks. They are based on the use of multiple antennas on both the transmitter and receiver sides. Such a structure allows the system to achieve high data rates without changing the bandwidth allocated to the signal or its transmission power. What's more, the use of more than one antenna on each side of the system provides diversity. Specifically, multiple replicas of the same information are transmitted on multiple channels with comparable power and independent fading, making it highly likely that at least one or more of the received signals will be unattenuated at any given time, allowing for good quality transmission. The result is an improvement in signal-to-noise ratio (SNR) and therefore bit error rate.Figure 34 shown the basic structure of a mimo system.

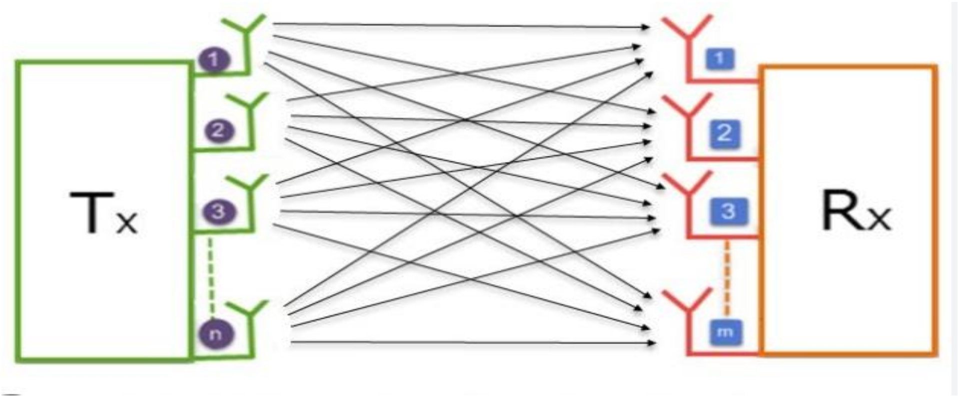


Figure 34: Basic structure of a MIMO system [67]

2.5.2. Diversity

The basic principle of diversity is that the receiver must have several versions of the transmitted signal, received on independent channels. Figure 35 shows two independent fading signals and the combined signal at the combiner's output. If the two signals are independent, then there is little chance of them fading at the same time. We can see that the combined signal has a higher average signal-to-noise ratio (SNR) than that received by each antenna: in other words, fading is less significant.

To achieve good diversity, we need a good combination of antennas to have independent fading signals, but also a good signal combination technique to maximize the average SNR at the output [66] .

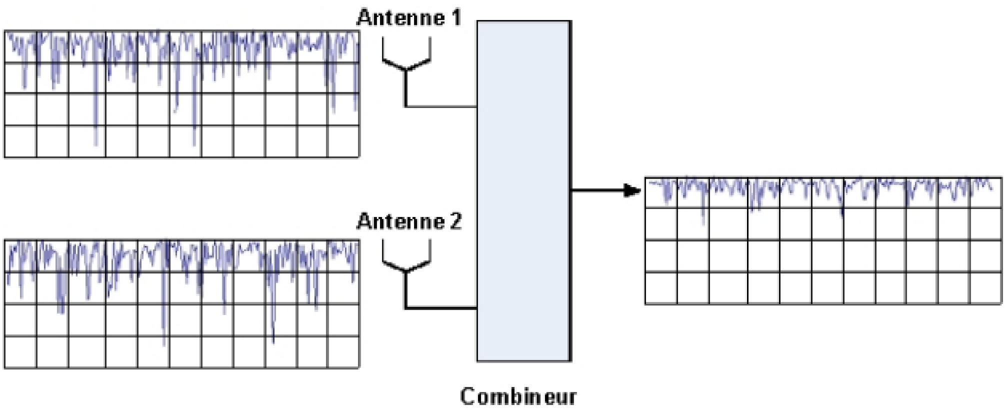


Figure 35 : Principal of diversity [66]

Among the diversity families, there are three types of antenna diversity: space, polarization and pattern diversity.

2.5.2.1 Space diversity

To receive decorrelated signals, the first approach is to physically spaced the antennas. The minimum distance to be observed is in the order of one time the wavelength of the signal for the mobile. It can reach more than ten times the wavelength of a base station, ensuring that it receives fading signals independently of each other. This technique has been called space diversity. Figure 36 illustrates how spatial diversity introduces decorrelation between two signals received by two spaced antennas. Two routes on each antenna are considered here. Each is the result of its own interaction with the environment. They were therefore independently affected by the environment and did not follow the same path either. Their amplitude and phase are then different. At reception, the signals received by each antenna are the result of the sum of these two trajectories. However, the differing positioning of the antennas induces a different phase-out on each of them. The received signals are all the more decorrelated as the antennas are spaced [68].

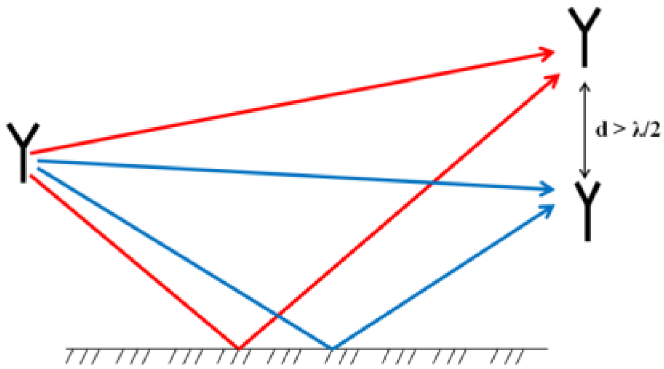


Figure 36: Space diversity [68]

2.5.2.2 Pattern diversity

Diagram diversity can be used when the diagrams of the two antennas are different. Using two antennas with different radiation diagrams, the signals reaching the antennas will be from different directions and therefore probably independent. Diagram diversity is never applied alone, it is usually combined with spatial diversity [66] as shown in figure 37.

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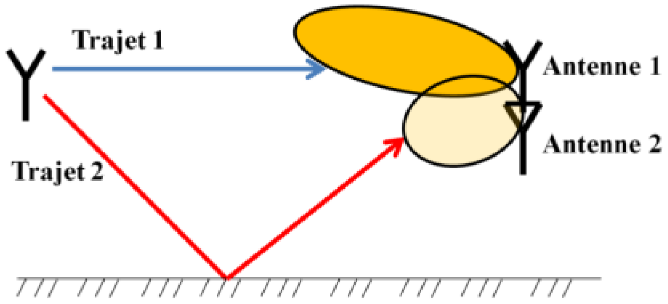


Figure 37: Pattern diversity [68]

2.5.2.3 Polarization diversity

Another type of diversity that we will be working with in the practical part of our project is the diversity of polarization.

Once adopted for mobile terminals (reduced size), the spacing between the elements of the antenna system required by spatial diversity has posed a structural problem which has encouraged the conversion to the diversity of polarization that does not require any separation.

A wave that spreads in a multi-track environment can undergo reflections that cause a change in its polarization according to the spread environment. The principle of polarization diversity is to use two antennas with complementary polarizations, a technique that serves to immunize the system against non-polarization adaptation and therefore against the evaporation of the transmitted signal. In most studies, polarized wire-type emitter antennas are used vertically. The combination of a pair of antennas with orthogonal polarizations ensures the correlation of the received signals and thus the recovery of the maximum possible power [69].

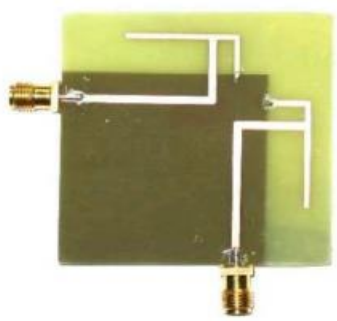


Figure 38:Example of polarization diversity:IFA antenna system (Inverted F antenna) [69]

2.6. Mutual coupling reduction

Mutual coupling is an electromagnetic phenomenon that is observed in many antennas arrays due to the interaction of fields between the antenna and the antenna array. the effect of mutual coupling has become more predominant over the years with the development of miniaturized radio transceivers that led to the emergence of small antenna arrays. When the spacing between the elements is very small the power radiated out by an antenna will be absorbed by the neighboring element of the array. This will affect the individual element pattern and thereby alters the overall radiation pattern of the array. The matching characteristics of the antenna elements are no longer constant and tend to change the input impedance of the array [70].

Mitigating mutual coupling between antennas in multi-antenna systems is crucial to maintain the desired performance of the antenna array. Here are several strategies commonly used:

2.6.1 Electromagnetic Band Gap (EBG) or neutralization structures

Electromagnetic Band Gap (EBG) structure was used to improve the isolation by blocking surface wave propagation. The EBG structure with no metallic vias or vertical components was formed by etching two slots and adding two connecting bridges to a convenient unipolar EBG unit cell [71].

2.6.2 Metamaterial structures

to concentrate electromagnetic fields and current near the antenna structure instead of spreading them along the antenna ground metamaterial structures are used. Because spreading of fields and currents results high mutual coupling between the antenna elements. The circuit size is reduced by using metamaterial technology also this structure produces better performance in both antenna and passive circuit applications [71].

2.6.3 Antenna elements of different types

The technique of orthogonal placement of antenna feeds/elements provides good isolation among the antenna elements. However, it will result in a dual-polarized system or polarization diversity. However, the true challenge will be the placement of the antenna elements in the same polarization and to obtain high isolation without any decoupling structures while maintaining compact dimensions [71].

2.7. Conclusion

This chapter has delved into the evolution and key components of modern wireless networks, particularly focusing on the transition to 5G technology. We have examined various network types, from WLANs to WWANs, and discussed the critical role of the communication chain, including link budget analysis and propagation channels. Advanced techniques such as MIMO and diversity have been highlighted for their contribution to enhancing transmission reliability and efficiency. Additionally, strategies for mitigating mutual coupling between antennas in multi-antenna systems were explored.

Chapter 3

Design of a Triband Dual-Polarized Antenna

Chapter 3: Design of a Triband Dual-Polarized Antenna

3.1 Introduction

5G communication networks require high-performance antennas capable of operating in several frequency bands. The Vivaldi antenna is a popular choice for 5G applications, high gain and directivity. In this chapter, we present the design of a Vivaldi tri-band dual-polarized operating in three specific frequency ranges crucial for 5G: 2.3-4 GHz, 3.5-3.7 GHz, and 5.8-5.9 GHz using CST Studio Suite software.

3.2 CST Microwave Studio Suite

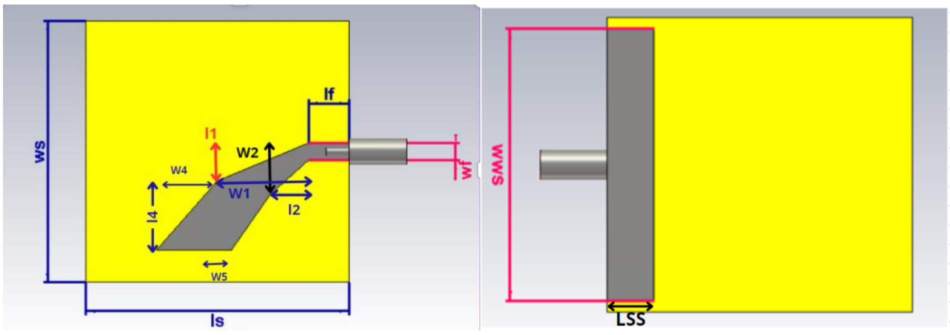
CST STUDIO SUITE electromagnetic simulation software, founded in 1992, represents the pinnacle of years of research and development into the most efficient and accurate electromagnetic simulation software. CST Microwave Studio is a software package for electromagnetic simulation of passive structures in three dimensions based on the resolution of Maxwell's equations using the Finite Integration Technique (FIT). This numerical method offers a discretization of space, enabling the direct description of all components of the systems described in three dimensions. This enables the application of the method to numerous electromagnetic problems, including those in the domains of statics, microwave frequencies, and time and frequency analysis. Moreover, in contrast to the majority of electromagnetic simulation software, CST discretizes the integral form of Maxwell's equations rather than their differential forms, which represents a significant distinguishing feature of this simulator.

CST Microwave Studio is a component of the CST DESIGN STUDIO suite and offers a range of diverse solvers, tailored to the specific type of application and the nature of the problem at hand. [72]

3.3 Design of a multi-band half Vivaldi Antenna

The antenna geometry is presented in figure 39**.** The structure is printed on the FR-4 Epoxy substrate with a dimension of 45.5x45.5mm^2, a relative permittivity of 4.4 and a thickness of 1.6mm. It is fed by a SMA connector.

The dimensions of the half Vivaldi antenna are as follows: lf=7 mm, wf=3 mm, L1=6.6 mm, L2=6 mm, L4=12 mm, W1=15.8 mm, W2=6.65 mm, W4=10.4 mm, W5=12.99 mm, h=1.6mm. The dimensions of the printed ground plane in the bottom is wws=42mm ,lss=5mm.



(a) (b)

Figure 39: (a)Dimensions of single band half Vivaldi antenna (b)View from below

Antenna structure dimensions affect significantly its performances. A parametric study is done in order to have a reflection coefficient less than -10 dB on the desired band.

a) Influence of the parameter wf

We will study the influence of the variation of the width wf, on the reflection coefficient as presented in Figure40. The length wf is varied from 3 mm to 3.5mm. These results show that reflection coefficient is slightly degraded with the decrease in wf. We observe that we have the best results for wf=3.5 mm. Therefore, we will keep this value for the rest of study.

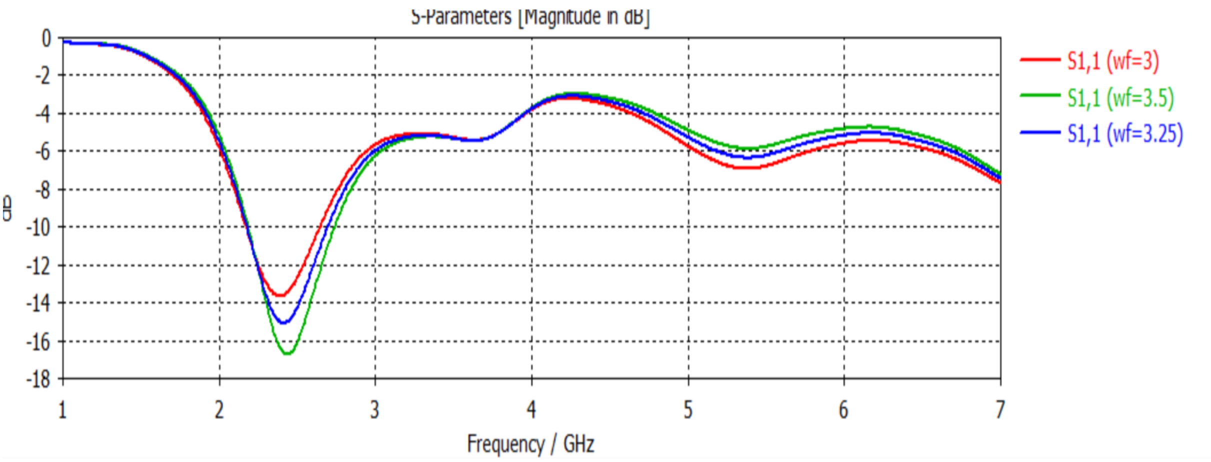


Figure 40: influence of wf

b) Influence of the parameter lf

We will study the influence of the variation of the length lf, on the reflection coefficient as presented in Figure 41. The length lf is varied from 5 mm to 6 mm. These results show that reflection coefficient almost did not change with the decrease in lf. We observe that we have the best results for lf=6 mm. Therefore, we'll stick with this value for now.

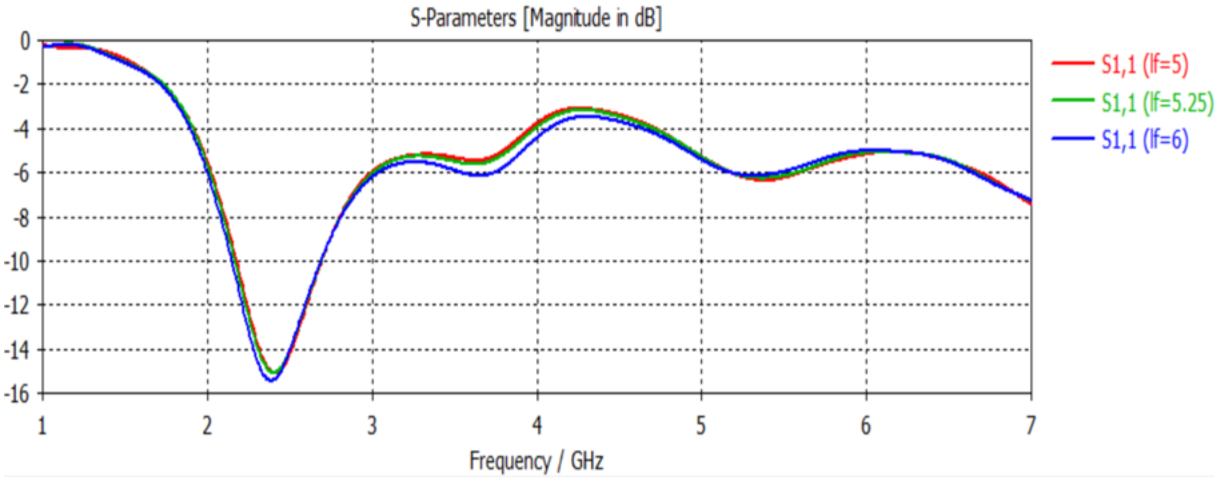


Figure 41: Influence of lf

c) Influence of the parameter l1

We will study the influence of the variation of the l1, on the reflection coefficient as presented in Figure 42. The length lf is varied from 4 mm to 7mm. These results show that the second resonance shift towards higher frequencies when l1 decreases. We observe that we have the best results for l1=7mm. Therefore, we'll stick with this value for now.

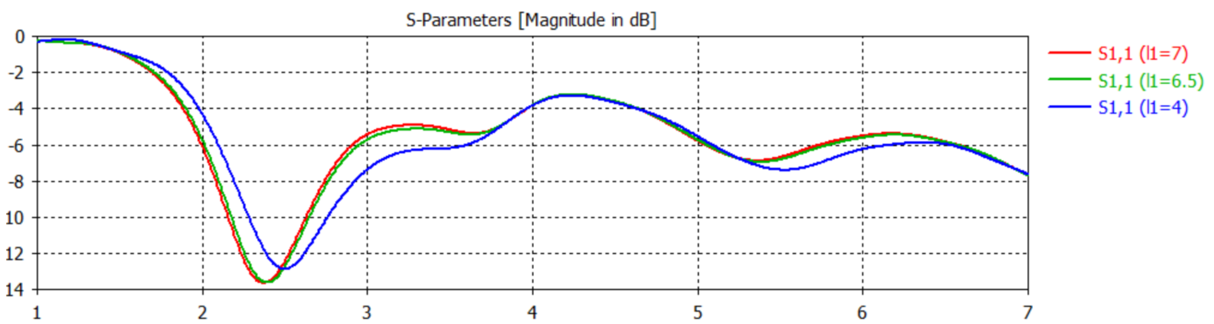


Figure 42: Influence of l1

Figure 43 shows the radiated gain of single band half Vivaldi antenna at the frequency of 2.4GHz. The value of the gain is 1.92dBi.

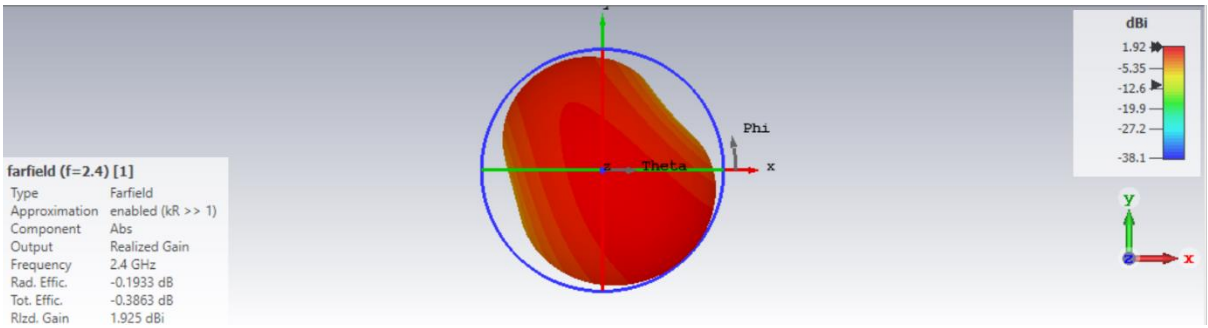


Figure 43: Realized gain of single-band half Vivaldi antenna

3.3.1 Introduction of the First Resonator

Adding a resonator to a single band half Vivaldi antenna can introduce a second resonance frequency as shown in figure 44.

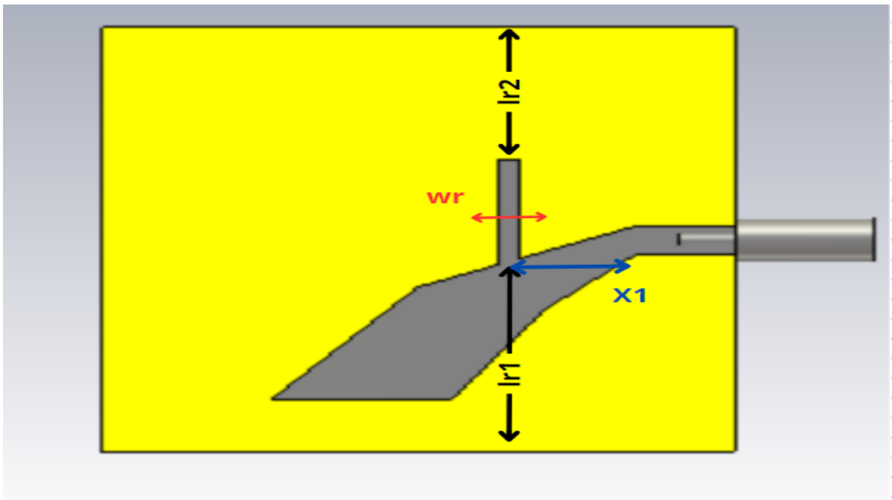


Figure 44 Antenna with single resonator

We will conduct a parametric study on various antenna dimensions while focusing on the reflection coefficient in order to achieve adaptation below -10 dB at 2.3-2.4 GHz and 3.5-3.7 GHz.

a) Influence of the parameter lf

We will study the influence of the variation of the length lf, on the reflection coefficient as presented in Figure 45. The length lf is varied from 6.5 mm to 7.5 mm. These results show that reflection coefficient is slightly degraded the second frequency with the decrease in lf while the first frequency is unchanged. We observe that we have the best results for lf=7.5 mm. Therefore we will keep this value for the rest of study. We note that this parameter helps the 3.5 GHz frequency to achieve adaptation below -10 dB.

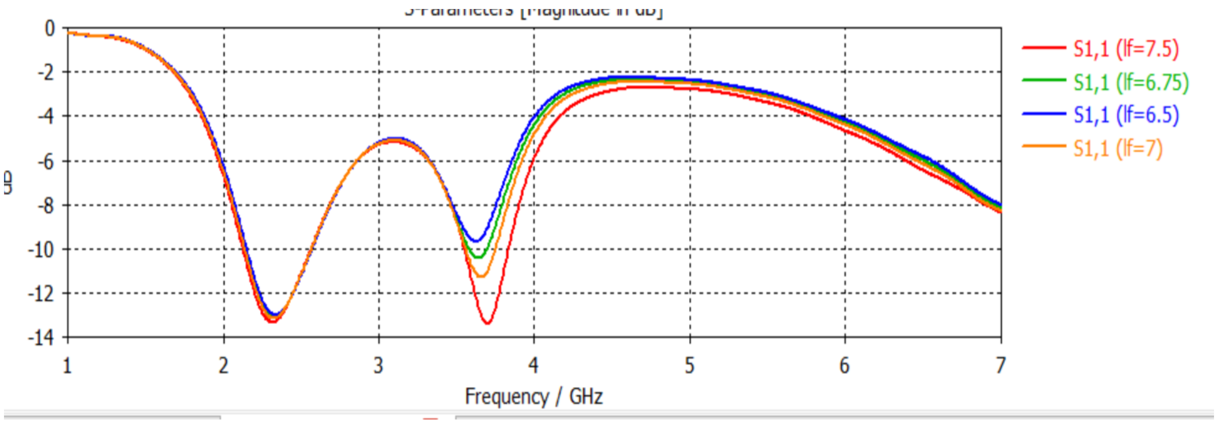


Figure 45:Influence of lf

b) Influence of the parameter lr1

We will study the influence of the variation of Lr1, on the reflection coefficient as presented in Figure 46. lr1 is varied from 3.5 mm to 5.5mm. These results show that the second resonance shift towards higher frequencies when lr1 decreases and the first resonance stay exchanged. We observe that we have the best results for lr1=5mm. Therefore, we will keep this value for the rest of study.

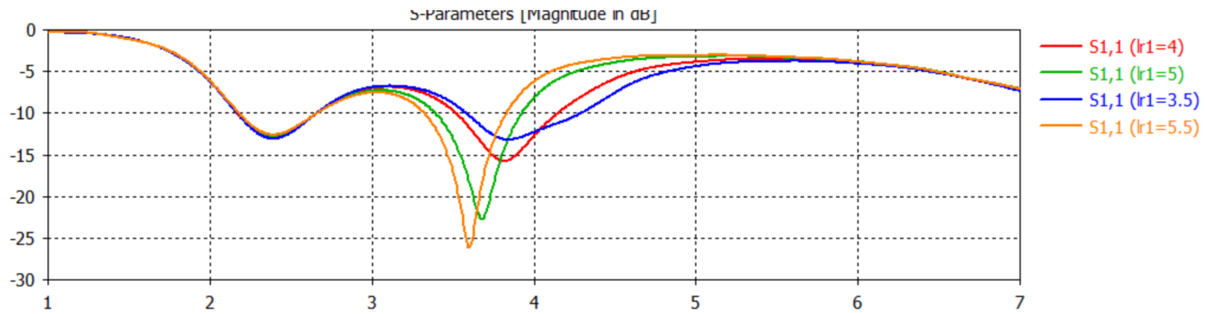


Figure 46: Influence of lr1

c) Influence of the parameter lr2

We will study the influence of the variation of lr2, on the reflection coefficient as presented in Figure 47. lr2 is varied from 4.5 mm to 6 mm. These results show that the reflection coefficient presents no modification. We observe that we have the best results for lr2=4.5 mm. Therefore, we will keep this value for the rest of study.

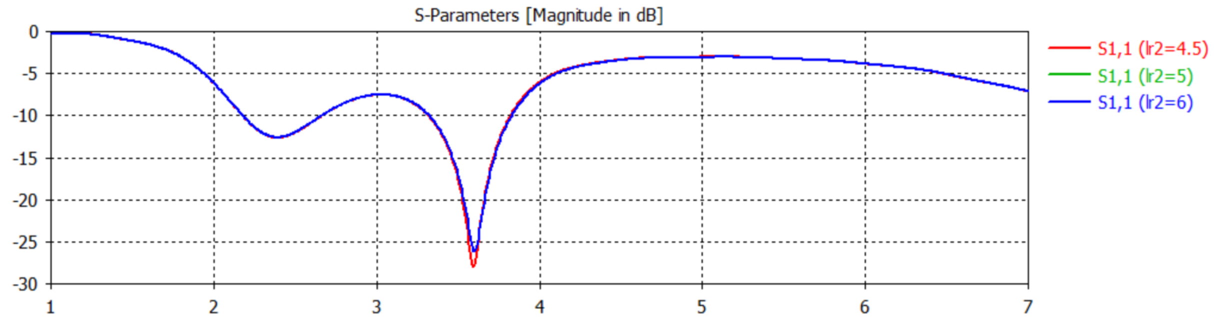


Figure 47: Influence of lr2

d) Influence of the parameter x1

We will study the influence of the variation of x1, on the reflection coefficient as presented in Figure 48. x1 is varied from 4.3 mm to 5.2mm. These results show that reflection coefficient presents a better matching with the decrease in x1. We observe that we have the best results for x1=5.2 mm. Therefore,we will assume this value remains unchanged for the duration of the study

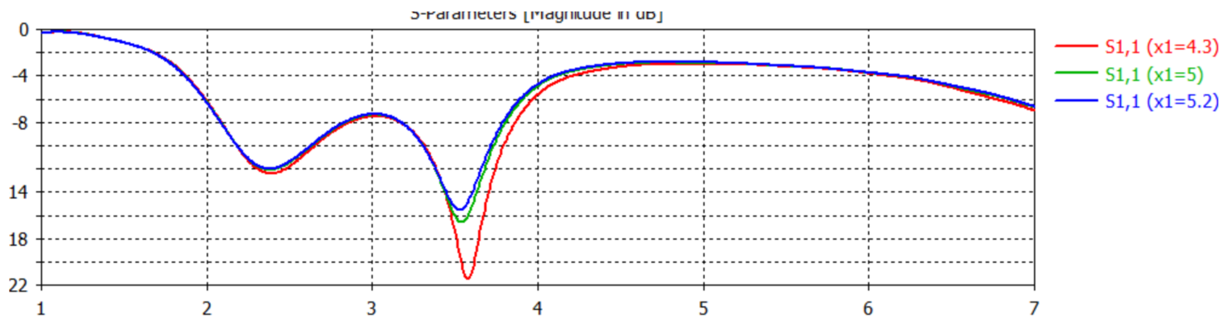


Figure 48:Influence of x1

3.3.2 Introduction of the second Resonator

We will introduce the second resonator to achieve triband functionality in the antenna design. This addition enables the antenna to operate effectively at three distinct frequency bands.

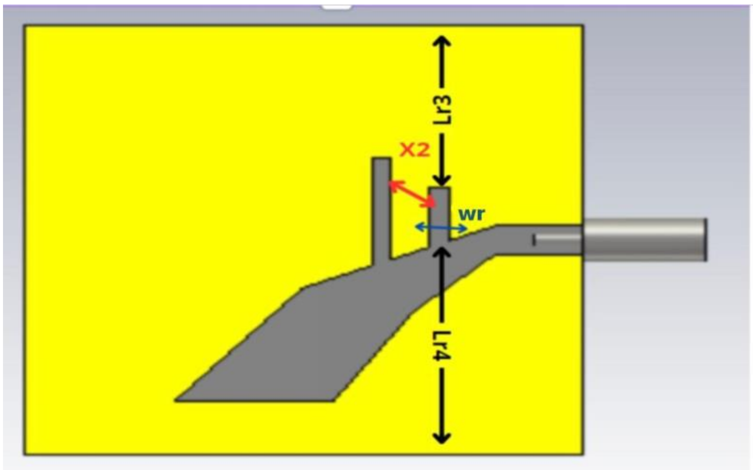


Figure 49:Antenna with two resonators

We will conduct a parametric study on various antenna dimensions while focusing on the reflection coefficient in order to achieve adaptation below -10 dB at 2.3-2.4 GHz , 3.5-3.7 GHz and 5.8-5.9GHz.

a) Influence of the parameter lr3

We will study the influence of the variation of lr3 on the reflection coefficient as presented in Figure 50. lr3 is varied from 6 mm to 7.1mm. These results show that reflection coefficient is well degraded with the decrease in lr3. We observe that we have the best results for lr3=7.1 mm. Therefore,we will hold this value constant for the remainder of the analysis.

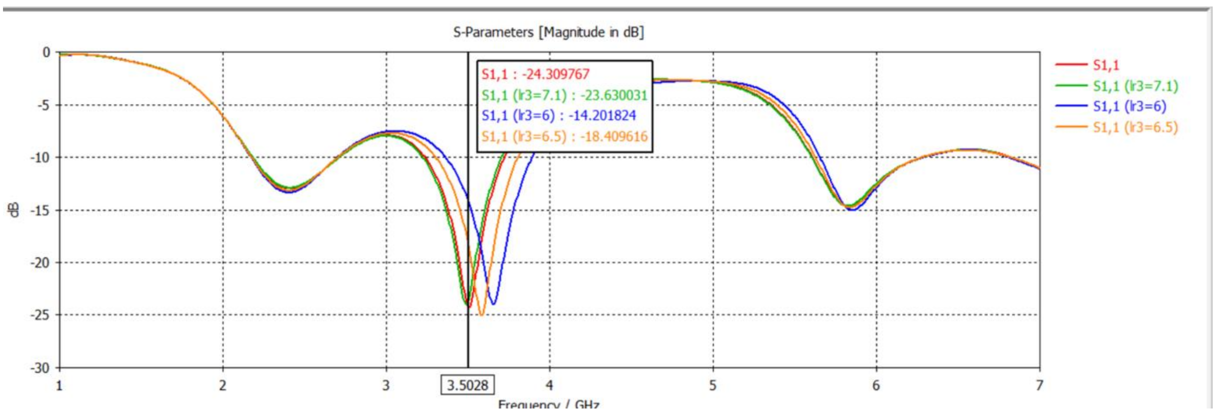


Figure 50: Influence of lr3

b) Influence of the parameter lr4

We will study the influence of the variation of lr4, on the reflection coefficient as presented in Figure 51. lr4 is varied from 4 mm to 5mm. The reflection coefficient has the same plot in this result so no matter what will the value.

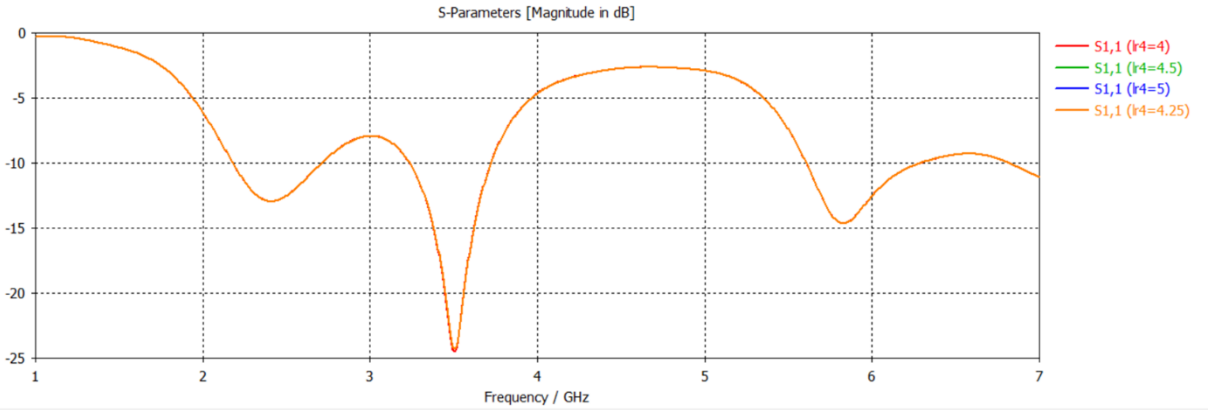


Figure 51: Influence of Lr4

c) Influence of the parameter x2

We will study the influence of the variation of x2, on the reflection coefficient as presented in Figure 52. x2 is varied from 2 mm to 3.5mm. These results show that reflection coefficient has an effect on the second and third resonances. We observe that we have the best results for x2=3 mm. Therefore, we will hold this value constant for the remainder of the analysis.

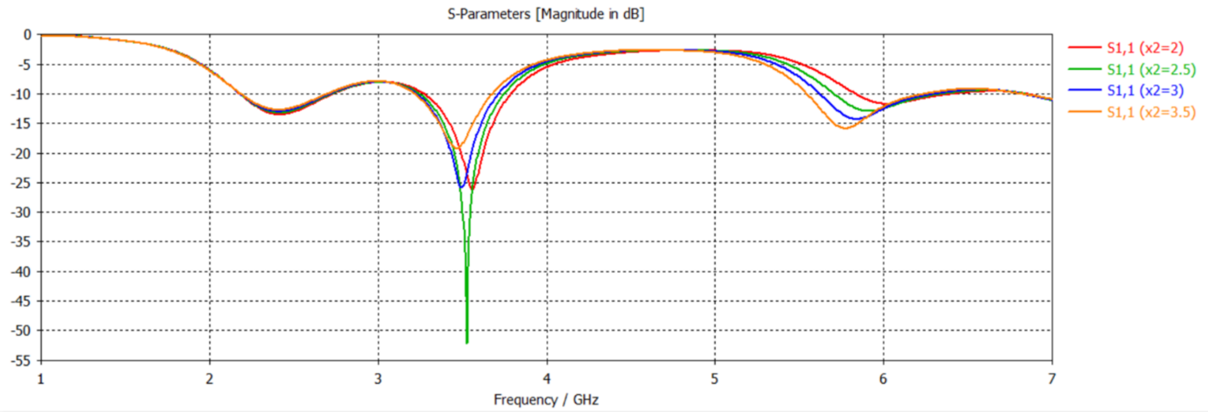


Figure 52: Influence of x2

d) Influence of the parameter wr

We will study the influence of the variation of wr, on the reflection coefficient as presented in Figure 53. wr is varied from 1.5 mm to 2mm. These results show that reflection coefficient affect the 2 higher frequencies by shifting the resonaces towards higher frequencies when wr decreases. We observe that we have the best results for wr=1.5 mm. Therefore,we will hold this value constant for the remainder of the analysis.

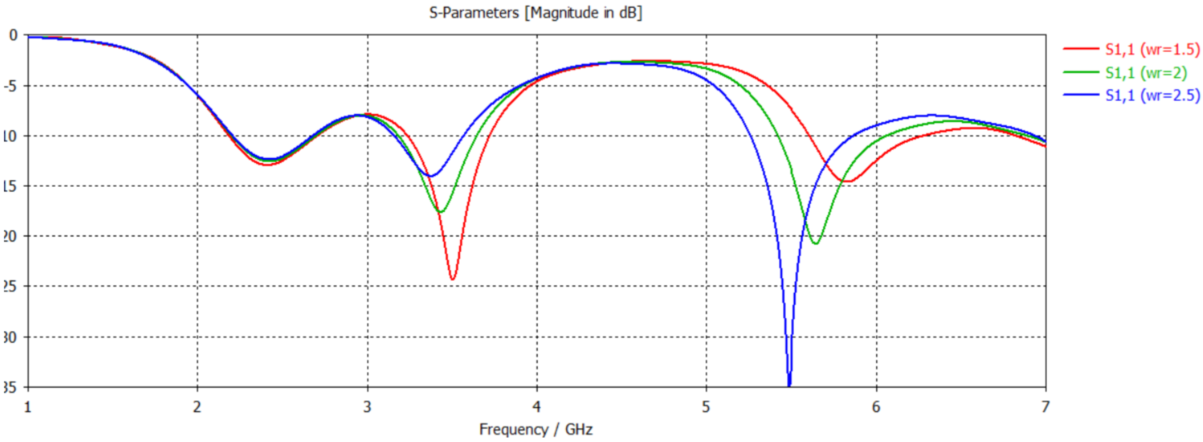


Figure 53:Influence of wr

3.4 Design of a multi-band dual polarized half Vivaldi antenna

A second half Vivaldi antenna is introduced using CST Microwave Studio, employing the translate and mirror options to achieve horizontal orientation. This configuration facilitates the realization of dual-polarization functionality.

The figure 54 shows the shape of dual-polarized antenna and S-parameters of dual Polarized triband antenna in figure 55. It can be seen that the structure operates in the 3 frequency bands:2.3-2.4GHz,3.5-3.7GHz ,5.8-5.9GHz with a transmission coefficient of -12dB,-15dB,-23dB respectively.

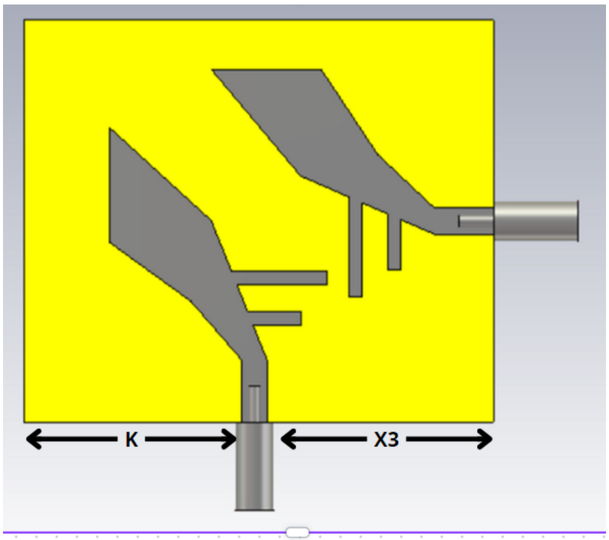


Figure 54: Dual polarized antenna

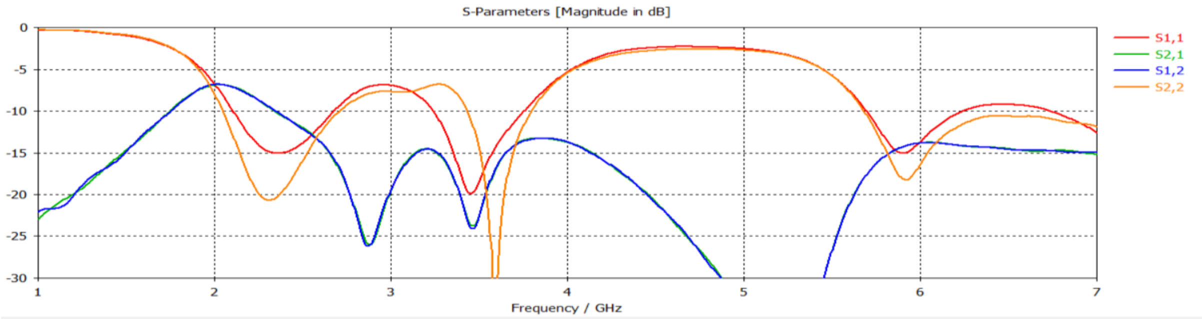


Figure 55: S-parameters of dual polarized antenna

We will carry out a parametric study on different antenna dimensions, focusing on the reflection coefficient dimensions of the antenna in order to achieve a match of less than -10 dB and a transmission coefficient as lower as possible.

3.4.1 Influence of l1 parameter

We will study the influence of the variation of l1, on the reflection coefficient as presented in Figure 56. l1 is varied from 6 mm to 7mm. These results show that reflection coefficient affects especially the third resonance by its soft on the higher frequencies when l1 decrease. We observe that we have the best results for l1=6 mm. Therefore, will hold this value constant for the remainder of the analysis.

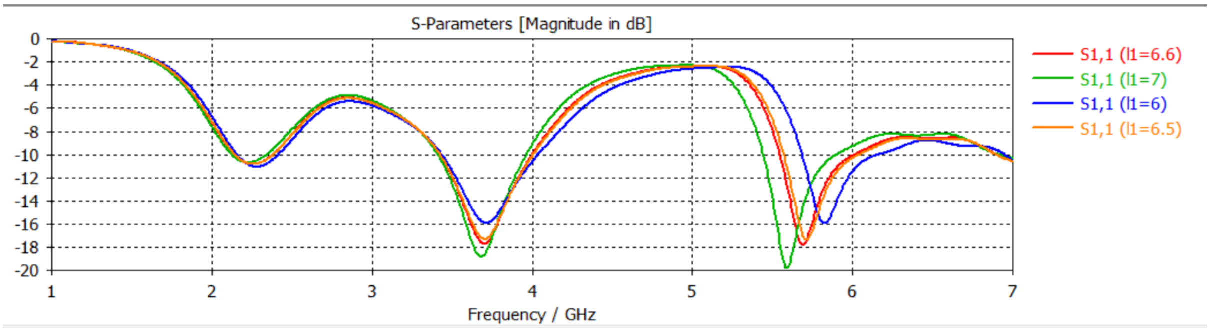


Figure: 56 :Influence of l1

3.4.2 Influence of l2 parameter

By varying l2 from 4.8 mm to 7mm, we obtain the result of the reflection coefficient as presented in Figure 57. These results show that it affects only the first resonance. We observe that we have the best results for l2=5mm. Therefore, we will hold this value constant for the remainder of the analysis.

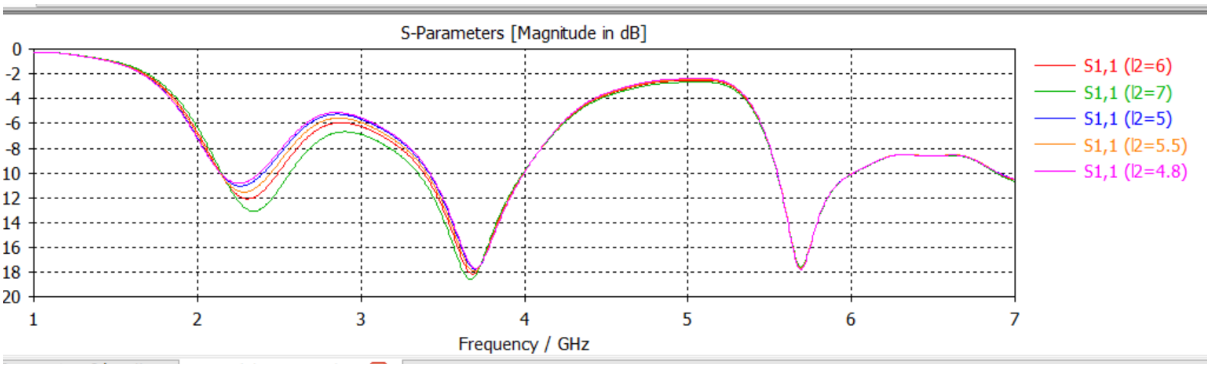


Figure 57*: Influence of l2*

3.4.3 Influence of lr1 parameter

We studied the influence of the variation of lr1, on the reflection coefficient as presented in Figure 58. lr1 is varied from 3.75 mm to 5mm. These results show that reflection coefficient affects significatly the third resonance when the 2 first resonances

remain unchanged.We observe that we have the best results for lr1=3.75mm. Therefore, we will hold this value constant for the remainder of the analysis.

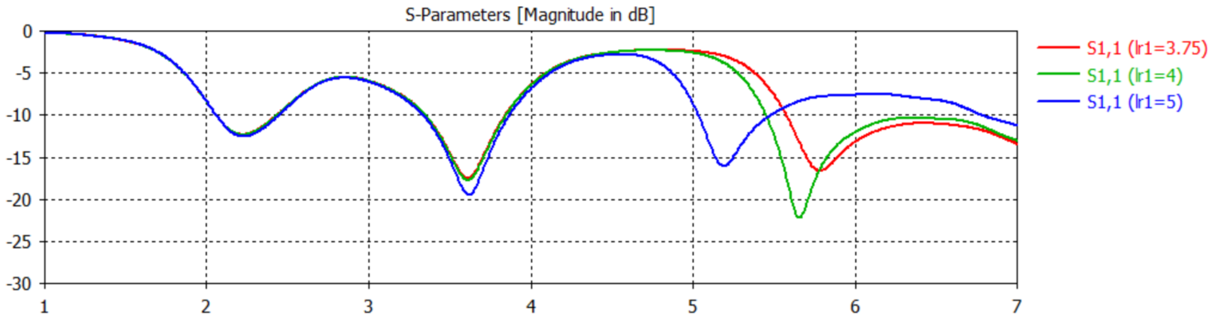


Figure 58*: Influence of lr1*

3.4.4 Influence of lr3 parameter

By varying lr3 between 4.5mm to 6mm, we obtain the results shown in Figure 59. The variation in lr3 has a significant influence on the antenna's performance in the frequency band 3.5-3.7GHz. We observe that we have the best results for lr3=5.5mm. Therefore,we will hold this value constant for the remainder of the analysis.

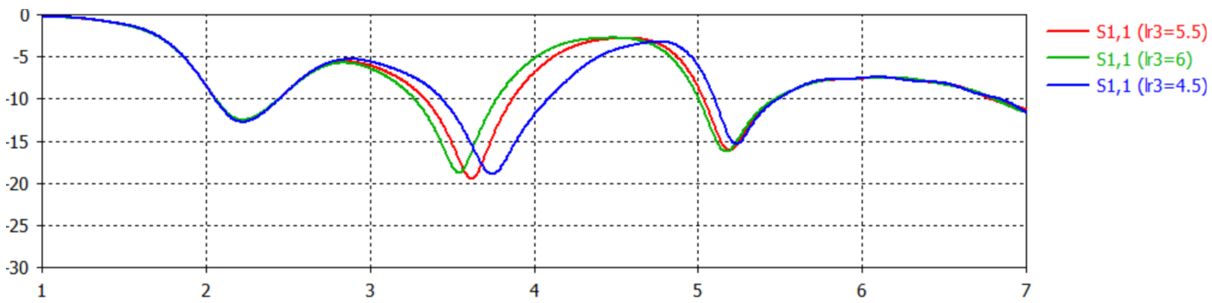


Figure 59 :Influence of lr3

3.4.5 Influence of w1 parameter

To study the influence of the w1 parameter, we'll vary it between 14mm to 15mm and then run the simulation to obtain the results shown in Figure 60. The variation in w1 has a significant influence on antenna matching. We'll take the value of W1 = 14.75mm.

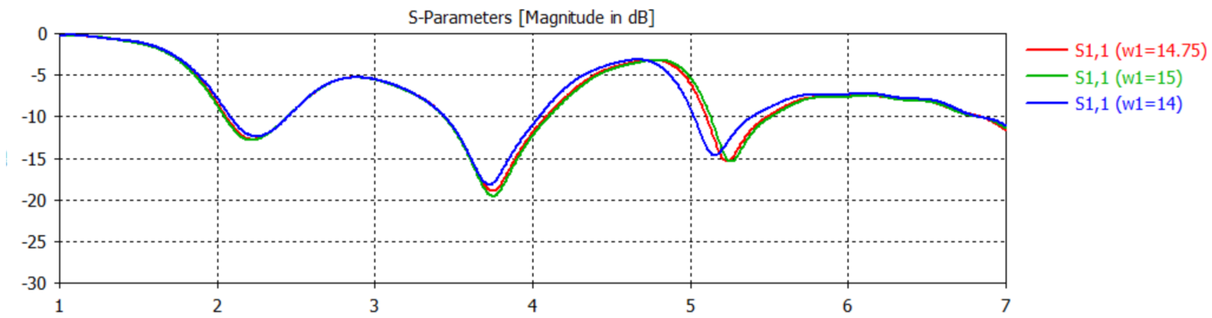


Figure 60 :Influence of w1

3.4.6 Influence of w2 parameter

To study the influence of parameter w2, we'll vary it between 7mm and 9mm as shown in figure 61 and then run the simulation to obtain the following results. The variation in w2 has a significant influence on first resonance. We'll take the value of w2 =8.6mm for the best adaptation.

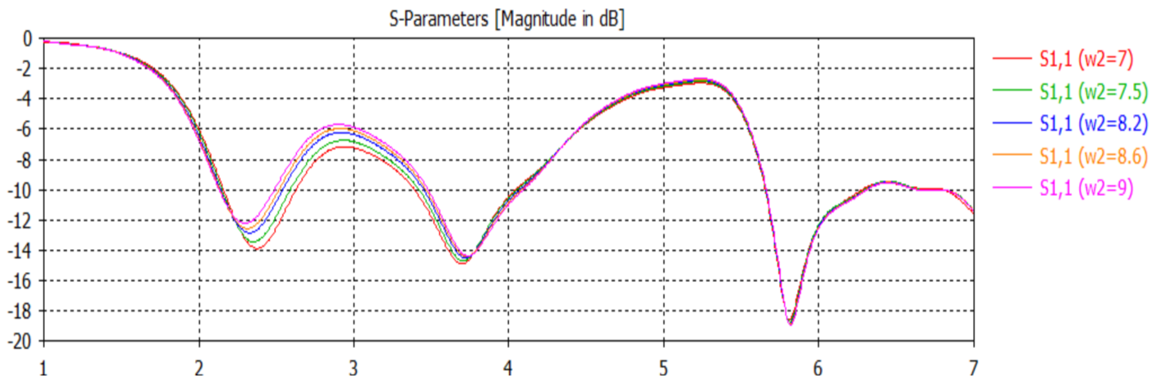


Figure 61*:* Influence of w2

3.4.7 Influence de x1 parameter

To study the influence of parameter x1, we'll vary it between 4mm and 5mm and then run the simulation to obtain the results shown in Figure 62. The variation in x1 has a significant influence on the third resonance by shifting the frequency band toward the

higher frequencies when x1 decreases. We'll take the value of x1= 4mm for the best results.

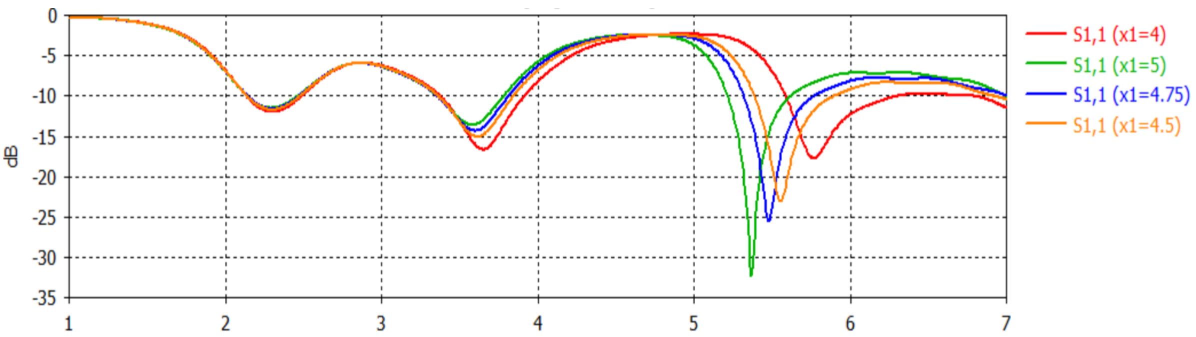


Figure 62: Influence of x1

3.4.8 Influence of x2 parameter

To study the influence of parameter x2, we'll vary it between 2mm and 4mm and then run the simulation to obtain the results shown in Figure 63. The variation in x2 has a significant influence on the two higher frequency bands. We'll take the value of x2= 2.5mm for the best results.

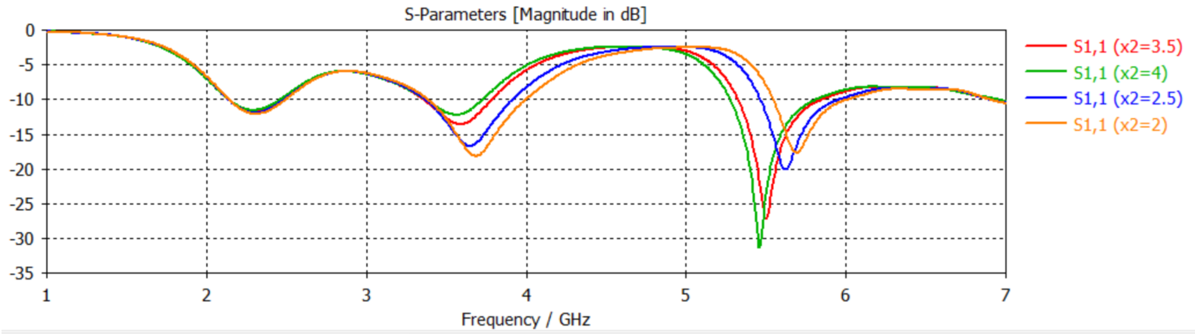


Figure 63 :Influence of x2

3.4.9 Influence of x3 parameter

In the final parameter, we will study the influence of the variation of x3,this parameter acts as distance between antennas on the reflection coefficient in figure 64 and the transmission coefficient in figure 65.x3 is varied from 10mm to 20mm.This results show that the reflection coefficient affect the second resonance and decrease in S21< -10dB.We observe that we have the best results for x3=20mm.

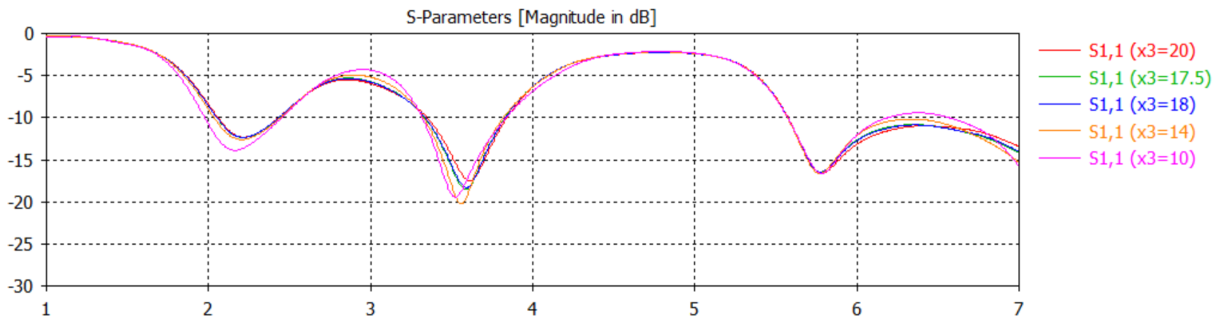


Figure 64: Influence of x3 on S11

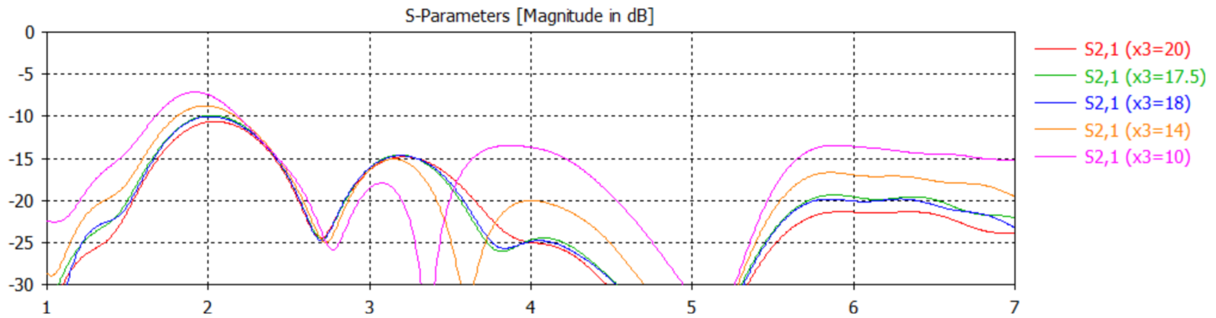
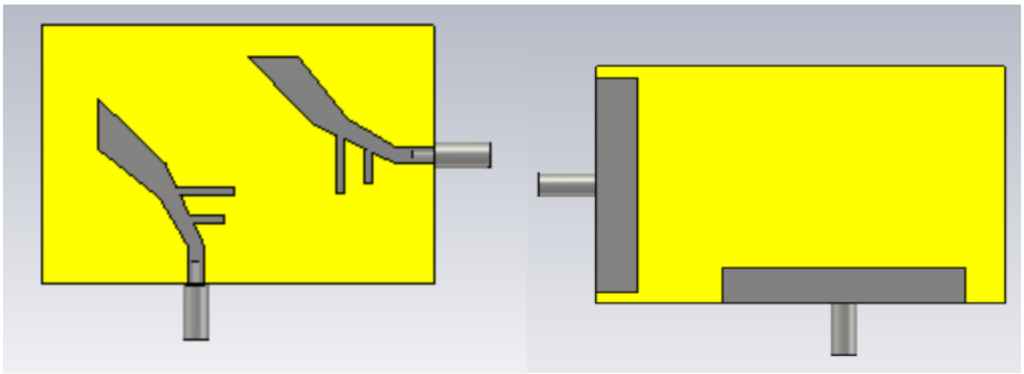


Figure 65: Influence of x3 on S21

3.5 Optimized structure

After the parametric study, the optimum structure obtained is shown in figure 66 with the following dimensions: l1=7mm, l2= 5mm, w1=14.75mm, w2=8.5mm, x1=4mm, x2=3.5mm, x3=20mm, lr1=3.75mm, lr3=5.5mm knowing that we did the simulation of lr2,lr4,w4 but they have no influence on the reflection coefficient .After running a simulation with this optimized structure.



(a) (b)

Figure 66: (a) optimized structure (b) View from below

The simulated |S11 | are shown in figure 67. Simulated results support three bands of operation: 2.3−2.4 GHz, 3.5−3.7 GHz, and 5.8− 5.9GHz. It is also observed, that the isolation is

-10.5dBi,-14.8dBi,-21dBi respectively for the three frequency bands and the gain values are 2.62dBi,3.92dBi,3.92dBi{ port1} 3.48dBi,3.42dBi,3.63dBi {port2}.

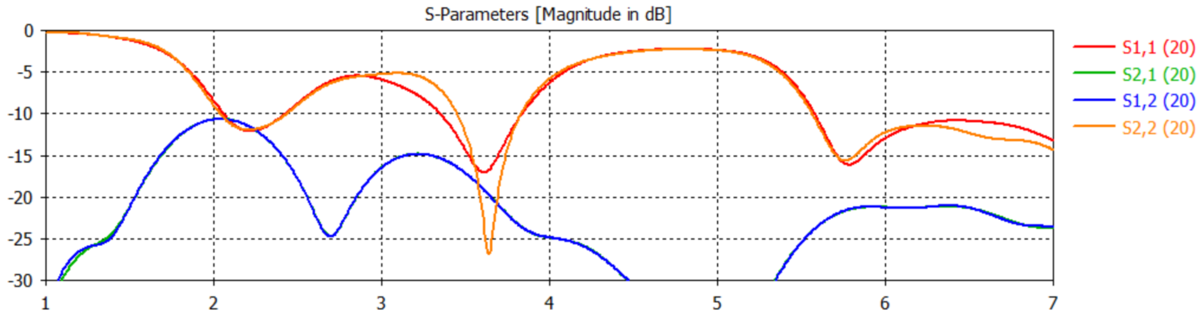
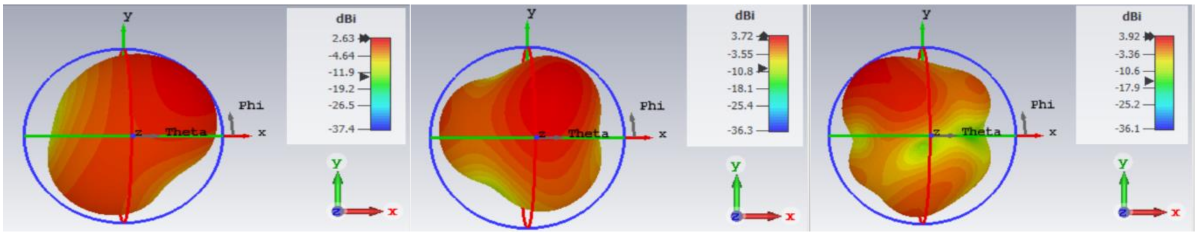


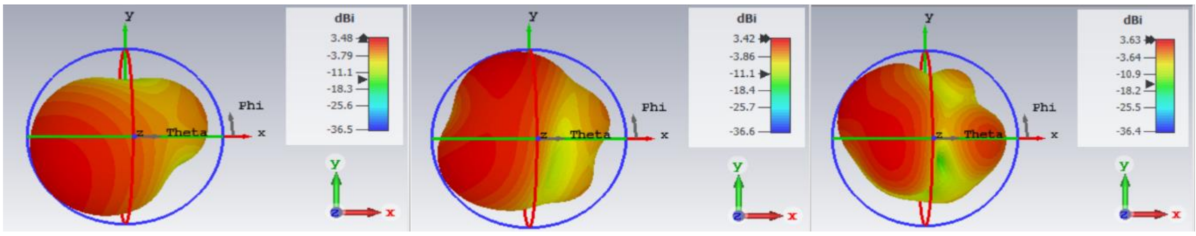
Figure 67 :S parameters of the proposed antenna

a)



2.3GHz **3.62GHz** **5.8GHz**

b)

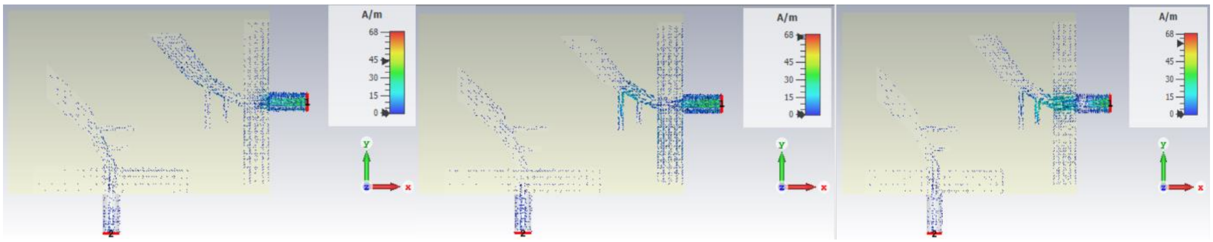


2.3GHz **3.62GHz** **5.8GHz**

Figure 68: a) Realized gain at 3 frequencies port1 b) Realized gain at 3 frequencies port2

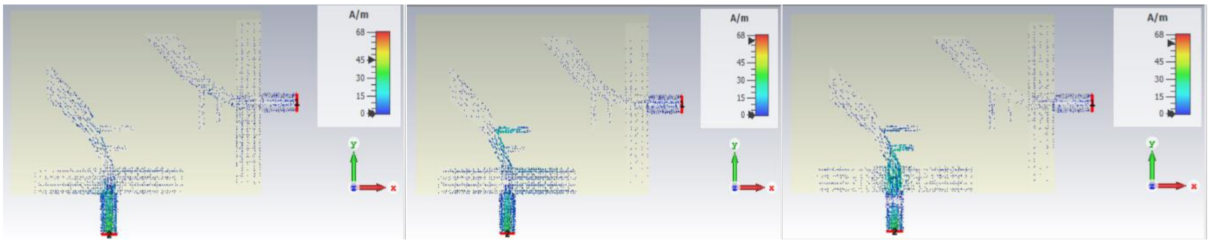
Figure 68 shows the realized gain at 3 frequencies in port 1 and 2 .It is observed that the realized gain of the antennas varies depending on the frequency and the port. At 2.3 GHz, port 1 has a realized gain of 2.62 dBi, while port 2 has a realized gain of 3.48 dBi. The realized gain also appears to vary depending on the frequency. For example, for port 1, the realized gain is highest at 3.62 GHz and lowest at 5.8 GHz.

a)



2.3GHz **3.62GHz** **5.8GHz**

b)



2.3GHz **3.62GHz** **5.8GHz**

Figure 69:a)Surface of the optimized structure port1 b) Surface current port2

Figure 69 shows the surface current of optimized structure port 1 and port 2 at the three frequencies. It is also observed that the higher frequency the higher current in all cases.

3.6 Conclusion

In this chapter, we started with an antenna single-band half vivaldi, then we added the two resonators step by step, after double polarization, parametric studies were carried out to obtain the optimal performance, simulation results were obtained using cst, which contains the reflection coefficients and the radiation diagram.

This structure is simple, inexpensive and operates in the 2.3-2.4 GHz ,3.5-3.7 GHz, 5.8-5.9 GHz and with a gain of 2.62dBi,3.73dBi3.92,dBi{port1},3.48dBi,3.42dBi,3.63dBi{port2} respectively.

General conclusion

This project began with a theoretical study of microstrip antennas, focusing on their operating principles and techniques for designing dual-polarized and multiband antennas. A literature review was also conducted, examining prior research to better understand advancements and ongoing challenges in antenna design, particularly in the context of wireless networks and 5G technology. This review highlighted the issue of multipath propagation and the need for solutions that can address these challenges.

In response, the project implemented polarization diversity and multiband capabilities to reduce the number of antennas required. We designed and simulated a tri-band, dual-polarized microstrip antenna using a half Vivaldi structure. The design process began with an antenna optimized for the 2.4 GHz frequency band, to which resonators for the 3.5 GHz and 5.8 GHz bands were added to achieve tri-band functionality. To enable dual polarization, an additional Vivaldi antenna was positioned orthogonally to the primary one, ensuring effective polarization diversity and satisfactory isolation between the antenna elements. The design and simulation were carried out using CST Microwave Studio Suite, allowing for precise modeling and performance evaluation of the antenna.

For future work, it would be advantageous to integrate Artificial Magnetic Structures (AMS) to further enhance the realized gain of the antenna. Additionally, constructing a physical prototype is recommended to validate the simulation results and assess the practical performance of the design. Such empirical validation would provide critical feedback and additional insights, guiding future improvements and developments in antenna technology for 5G applications.

Bibliography

[1] Abdi,M .Analysis of Wideband Iris-Fed Microstrip Patch Antenna Based on MOM-GEC Method, Ecole nationale d'Ingénieurs de Tunis, 6 Dec 2023.

[2] Singh I,Tripathi V S ."Microstrip Patch Antenna and its application a survey," Comp. Tech.Appl.Vol2 (5), no. 1595-1599., 2011.

[3] Cormier,G. Antennes microruban, 2012: Université de Moncton.

[4] "El-Pro-Cus," [Online]. Available: https://www.elprocus.com/microstrip-antenna/.

[5] Madani Yousfi,Z. Reseaux d'antennes vivaldi pour des applications medicales., Universite Abou Bakr Belkaid - Tlemcen.

[6] Meriah, D. Z. kerati, F. Z. Marouf and S. M ."New tapered slot vivaldi antenna for UWB applications," 2012 24th International Conference on Microelectronics (ICM), 2012.

[7] Champion,J .Etude d'antennes compactes à large bande de fréquence à gradient d'indice, brest: Université de Bretagne occidentale, 2022.

[8] Kumar G , Malik R K. "Design and simulation of half Vivaldi & Full Vivaldi antenna for mobile applications," International Journal of engineering research & technology (IJERT), 2017.

[9] Balanis Constantine A. Antenna Theory Analysis And Design, 3eme Édition John Wiley And Sons, 2005, P. 813.

[10] Guerraoui. M, Conception d'une nouvelle antenne pour une application GPR, Guelma, 2022.

[11] Fernandes da Silva Junior.P,Al .Fractal and polar microstrip antennas and arrays for wireless communications, IntechOpen, october 2019, pp. 1-20.

[12] Aliyu Rufai Yauri, Abdullahi SB Mohammed and A. M. Kabir, "Review of feeding techniques for microstrip patch," vol. 178, no. 27, June 2019.

[13] Leo Pauline S, Ganesh Babu T R."Design and analysis of compact dual band U-Slot microstrip," International Journal of Engineering & Technology, no. 7 (3.1) (2018) 17-19, 2018."

[14] Bousaha,S.Magister en Télécommunications, GUELMA: Département Electronique et Télécommunications, 2012

[15] Pozar,D,M, "Microstrip antenna aperture-coupled to a microstripline," vol. 21, 1985.

[16] Picon O, coll. Les antennes Théorie, conception et applications, PARIS: Dunod, 2009.

[17] Roubine E,Bolomey J Ch.Introduction générale antennes, paris france: Masson, 1978.

[18] Valleau,M,J.Miniaturisation d'antennes tres large bande pour applications spatiales, These doctorat de l'université de Toulouse, 1 décembre 2016.

[19] Elkilani,S .Étude, Conception et Réalisation des antenne patches et Pifa multi-bandes, Faculté des sciences et techniques settat, 2020/2021.

[20] Berkat,L.Modélisation des antennes microrubans multicouches par une approche neurospectrale, Batna: Université Batna 2 – Mostefa Ben Boulaïd, 2022.

[21] Kang H I,Song J T .“Electrically tunable rectangular microstrip antenna.”.

[22] J.-C,Langer C, "IEEE Microwave and wireless components letters," 2003.

[23] Moumed A,Tiab N.Conception d'une nouvelle antenne multi-bandes à polarisation circulaire, Université 8 Mai 1945 – Guelma: Memoire de pfe Pour l’obtention du diplôme de Master Académique, 2021.

[24] Bernhard J T ,Kiely E , Washington G."A smart mechanically actuated two-layer electromagnetically coupled microstrip antenna with variable frequency, bandwidth, and antenna gain},," vol. 49, no. 4, 2001.

[25] Sheta A ,Mahmoud S F.A Widely tunable compact patch antenna., IEEE Antennas and Wireless propagation letters 7, 2008.

[26] Kokotoff D M, Waterhouse R B,Birtcher C R , Aberle J."Annular ring coupled circular patch with enhanced performance," vol. 33, Nov 20 1997.

[27] Azzaz Rahmani S, "Analyse et conception des antennes imprimees," Juillet 2013 .

[28] Hafedh Ben Ibrahim G, Analyse et conception des antennes fractales applications aux télécommunications large bande, 18 Juillet 2007.

[29] Vaziri,P,M .2013 21st Iranian conference on electrical engineering (ICEE), 2013.

[30] Gao S, Joshua L W Li,Leong M S,Yeo T S ."Dual-polarized slot-coupled planar antenna with wide bandwidth,"," IEEE Transactions on Antennas and Propagation, vol. 51, no. 3, pp. 441-448, 2003.

[31] Serra A,Buffi M ,Rodriguez-Pino and G. Manara, "Dual-polarised slot-coupled patch antenna excited by a square ring slot," IET Microwaves Antennas & Propagation, vol. 5, no. 5, pp. 605 - 610, May 2011.

[32] Saraswat K,Harish A R ."Single feed dual polarized crossed slot antenna for tri-band operation," *2018* International Symposium on Antennas and Propagation (ISAP), 2018.

[33] Jie Lu, Kuai Z,Zhu X, Zhang N. "A High-Isolation dual-polarization microstrip patch antenna with quasi-cross-shaped coupling slot," IEEE transactions on antennas and propagation, vol. 59, no. 7, p. 2713, July 2011.

[34] Li W, Xia Z , You B ,Liu Y ,Liu Q H ."Dual-polarized H-Shaped printed slot antenna," IEEE Antennas and wireless propagation letters, 2017.

[35] Gao S, Le-Wei Li J , Leong M S ,Yeo R."A Broad-Band Dual-Polarized microstrip patch antenna with aperture coupling," IEEE transactions on antennas and propagation, vol. 51, no. 4, p. 898, April 2003.

[36] Civerolo M ,Arakaki D ."Aperture coupled patch antenna design methods," IEEE 2011 IEEE Antennas and Propagation, p. 876–879., 2011.

[37] Du Toit L & Cloete J H" Dual polarized linear microstrip patch array," Proceeding of Antennas and Propagation Society International Symposium, vol. 25, pp. 810- 813, June 1987.

[38] Zhong S-S, Yang X-X ,Gao S ,Cui J-H ."Corner-fed micostrip antenna element and arrays for dual-polarization operation," IEEE Transactions on Antennas and Propagation, vol. 50, no. 10, pp. 1473-1480., 2002.

[39] Gao S, Zhong S ."A dual-polarized microstrip antenna array with high isolation fed by

coplanar network," Microwave and Optical Technology Letters., vol. 19, no. 3, pp. 214-216, 20 october 1998.

[40] Woelders K &Granholm J, " Cross-Polarization and sidelobe suppression in dual linear polarization antenna arrays," IEEE Transactions on Antennas and Propagation, vol. 45, no. 12, pp. 1727-1740., December 1997.

[41] Gosalia K & Lazzi G ."Reduced size, dual-polarized microstrip patch antenna for wireless communications.," IEEE Transactions on Antennas and Propagation, vol. 51, no. 9, pp. 2182-2186., September 2003

[42] Deshmukh A A, Verma P ."Crescent Shape microstrip antenna for dual polarized multi-band response," 2019.

[43] Deshmukh A A, Verma P . "Multi-band Dual Polarized variations of modified circular microstrip antennas," 2019.

[44] Yuan L ,Liang Y, Jian-Feng L, Duo-Long W , Xiu Z ."Triband Dual-Polarized dipole Antenna with controllable Bandwidths for 5G/LTE Applications," vol. 23, 2024.

[45] Chakrabarti S, Chakraborty A ."Dual-band dual-polarised microstrip antenna with improved inter-port isolation," *IET Microwaves Antennas ,Propagation* , vol. 55, no. 5, pp. 239-240, March 2019.

[46] Liu J ,Liu H,Dou X ,Tang Y , Zhang CH ,Wang L , Tang R ,Yin Y .""A low profile, dual-band, dual-polarized patch antenna with antenna-filter functions and its application in MIMO Systems,"," IEEE Access, vol. 9, 2021.

[47] Zhou L,Fang Sh , Jia X ."Dual-band and dual-polarized circular patch textile antenna for on-/off-body WBAN applications," IET,Microwaves Antennas ,Propagation, vol. 14, no. 7, pp. 643-648, June 2023.

[48] [Online]. Available: https://www.oreilly.com/library/view/ccna-wireless-640-722/9780133445725/ch05lev2sec1.html.

[49] ElHajj M .Caractérisation et modélisation du canal de propagation indoor pour les réseaux WLAN/WPAN multi-bandes, INSA de Rennes; Université Libanaise, 2020.

[50] Islam M, Jin Sh ."An overview research on wireless communication network," Networks, 2019.

[51] Isah A A, Adamu A , Awal A , Babajo A A, "A review of wireless networks: wlan security and threats," Advance journal of science, Engineering and technology, 2022.

[52] Shimo M H U .Wireless internet connectivity: 5G and Wi-Fi 6, Metropolia university of applied sciences, 2022.

[53] Nguyen L ."Evolution of Wireless technology: From 1G to 5G," Asian Journal of Applied Science and Technology (AJAST) , pp. 68-73, 2023.

[54] Hossain S ."5G Wireless communication systems," American Journal of Engineering Research (AJER).

[55] [Online]. Available: https://inseego.com/nz/resources/5g-glossary/what-is-wwan/.

[56] [Online]. Available: https://ytd2525.wordpress.com/2021/03/29/rf-and-5g-new-radio-top-5-questions-answered/.

[57] 2023. [Online]. Available: https://nybsys.com/5g-bands/.

[58] Baylan,A .Sub-6 GHZ 5G Mimo antenna, Master of science in electrical and electronic, 2023.

[59] Zhang H, Liu Na, Chu X,Long K, Aghvami A .Network slicing based 5G and future mobile networks: Mobility, Resource Management, and Challenges, IEEE Communications Magazine, 2017.

[60] Choumane,A .Synthèse d’un canal de propagation par système multiantennes pour la caractérisation de terminaux mobiles à diversité, Universite de limoges, 2011.

[61] Bellil,M,I .Développement d’un outil de calcul du bilan de liaison pour système de transmission par Faisceau Hertzien, l’université de tlemcen , 2025.

[62] Bennaceur S,Bellahsene H .Etude et modélisation de canaux SISO dans le cas Outdoor, Université Abderrahmane Mira Bejaia, 2012-2013.

[63] Shannon,C. "Communication in the Presence of Noise," *Proceedings of the IRE*, 1949.

[64] Picol,S .Conception et réalisation de la partie numérique d’un simulateur matériel pour les canaux de propagation Mimo, INSA de Rennes: Sciences de l’ingénieur, 2007.

[65] Ahamed M M, Saleh F ."Propagation factors affecting the performance of 5G millimeter wave radio channel," in IEEE International conference on electro information technology (EIT), 2016.

[66] Diallo,A .Systèmes multi-antennes pour diversité et MIMO, Université Nice Sophia Antipolis, 2007.

[67] [Online]. Available: https://www.oreilly.com/library/view/ccna-wireless-640-722/9780133445725/ch05lev2sec1.html.

[68] Mouffok,L, Conception de syst`emes multi-antennes multi-bandes pour terminaux mobiles LTE, Telecom ParisTech, 2013.

[69] Krouka W, Fenni S .Évaluation de la diversité d’antenne en polarisation, ecole nationale polytechnique, 2015.

[70] Chandu D, Karthekiyan S S, Phani Kumar K V .Reduction of mutual coupling in a two element patch antenna array using sub-wavelength resonators, IEEE, 2015.

[71] Jayanthi K, Kalpana A M ."Mutual coupling reduction techniques between MIMO antennas for UWB applications," International Journal on Recent and Innovation Trends in Computing and Communication, 2017.

[72] Douchet L, Antony N .Electronique MP, 2007.

[73] Liu W-C, Huang C-C,Wu C-M ."Dual-polarised single-layer slotted patch antenna.," IEE Electronics Letters, vol. 40, no. 12, pp. 717-718, 10 june 2004.

[74] "passive-components," [Online]. Available: https://passive-components.eu/what-are-filter-s-parameters/?fbclid=IwZXh0bgNhZW0CMTAAAR1KyqhB-AjMVF8NTuOHUxOeQam2mtzZWbK-4f_eCzuaJUAj-ZWuaujzCXA_aem_6uof11_aELcxNMpQVY6PFA.

[75] Khaleel,A. "Desing tri-band single and dual patch array antenna with band supression," Research gate, 2012.