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## Entitled

# Design and Performance Enhancement of a Microstrip Patch Antenna for 2.4 GHz

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for the success.*

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facilitate the implementation of this work.*

# DEDICATION

*In the Name of Allah, the Most Merciful, the Most Compassionate  
all praise be to Allah, the Lord of the worlds; and prayers and peace  
be upon Mohamed His servant and messenger.*

*Before all and foremost, We must acknowledge Our limitless thanks  
to Allah, the Ever-Magnificent; the Ever-Thankful, for His help We  
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realization of this work.*

**ABDELOUAHAB GHRISSI ,NASREDDINE DJEGHBALA**

## **Abstract**

The field of wireless communications has witnessed rapid development in recent years, which necessitated the development of antennas capable of keeping up with the requirements of modern systems, in terms of performance, efficiency, and size. Among the most prominent of these antennas are Patch Antennas, which are characterized by light weight, ease of fabrication, low cost, and their ability to operate in multiple frequency bands with good radiation performance.

This thesis aims to study, design, and analyze the performance of patch antennas using advanced simulation techniques. Emphasis was placed on analyzing basic antenna characteristics such as bandwidth, reflection coefficient (S11), and VSWR, as well as evaluating the impact of geometric modifications on the overall performance. HFSS software was used to perform accurate simulations of two designs: A conventional patch antenna and a modified patch antenna.

The simulation results showed that the proposed modifications improved the radiation characteristics, making the modified design suitable for multiple applications such as Wi-Fi and IoT systems particularly those operating at 2.4GHz.

Keywords:

Patch antennas, HFSS, bandwidth, S11 reflection coefficient, VSWR, feeding techniques, antenna design.

## Resumé

Le domaine des communications sans fil a connu un développement rapide ces dernières années, ce qui a nécessité la mise au point d'antennes capables de répondre aux exigences des systèmes modernes en termes de performance, d'efficacité et de taille. Parmi ces antennes, les plus importantes sont les antennes patch, qui se caractérisent par leur légèreté, leur facilité de fabrication, leur faible coût et leur capacité à fonctionner dans plusieurs bandes de fréquences avec de bonnes performances de rayonnement.

Ce Mémoire vise à étudier, concevoir et analyser les performances des antennes patch à l'aide de techniques de simulation avancées. L'accent a été mis sur l'analyse des caractéristiques fondamentales de l'antenne telles que la largeur de bande, le coefficient de réflexion (S11) et le ROS, ainsi que sur l'évaluation de l'impact des modifications géométriques sur les performances globales. Le logiciel HFSS a été utilisé pour simuler avec précision deux conceptions : Une antenne patch conventionnelle et une antenne patch modifiée.

Les résultats de la simulation ont montré que les modifications proposées amélioreraient les caractéristiques de rayonnement, ce qui rend la conception modifiée adaptée à de multiples applications telles que le Wi-Fi et les systèmes IoT en particulier ceux fonctionnant à 2.4GHz.

Mots-clés :

Antennes patch, HFSS, bande passante, coefficient de réflexion S11, VSWR, techniques d'alimentation, conception d'antenne.

## ملخص

شهد مجال الاتصالات اللاسلكية تطورًا متسارعًا خلال السنوات الأخيرة، مما استدعى تطوير هوائيات قادرة على مواكبة متطلبات الأنظمة الحديثة، من حيث الأداء، الكفاءة، والحجم. ومن بين أبرز هذه الهوائيات نجد الهوائيات الرقعية (Patch Antennas)، التي تتميز بخفة الوزن، سهولة التصنيع، وانخفاض التكلفة، إلى جانب قدرتها على العمل ضمن نطاقات تردد متعددة مع أداء إشعاعي جيد.

تهدف هذه المذكرة إلى دراسة وتصميم وتحليل أداء الهوائيات الرقعية باستخدام تقنيات المحاكاة المتقدمة. تم التركيز على تحليل الخصائص الأساسية للهوائيات مثل عرض النطاق الترددي، معامل الانعكاس (S11)، ونسبة الموجات المرتردة (VSWR)، بالإضافة إلى تقييم تأثير التعديلات الهندسية على الأداء العام. تم استخدام برنامج HFSS لإجراء محاكاة دقيقة لتصميمين: هوائي رقعي تقليدي وآخر معدل.

أظهرت نتائج المحاكاة أن التعديلات المقترحة ساهمت في تحسين الخصائص الإشعاعية، مما يجعل التصميم المعدل مناسبًا لتطبيقات متعددة مثل أنظمة Wi-Fi وإنترنت الأشياء (IoT) وخاصة تلك التي تعمل بتردد 2,4GHz. الكلمات المفتاحية:

الهوائيات الرقعية، HFSS، عرض النطاق الترددي، معامل الانعكاس S11، VSWR، تقنيات التغذية، تصميم الهوائيات.

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# List of Abbreviations

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## List of Abbreviations

Wi-Fi: Wireless Fidelity.

WLAN: Wireless Local Area Network.

WiMAX: Worldwide Interoperability for Microwave Access.

MIMO: Multiple Input Multiple Output.

HFSS: High-Frequency Structure Simulator.

CST: Computer Simulation Technology.

PCB: Printed Circuit Board.

VSWR: Voltage Standing Wave Ratio.

AM: Amplitude Modulation.

FM: Frequency Modulation.

IEEE: Institute of Electrical and Electronics Engineers.

ISM: Industrial, Scientific, and Medical.

IoT: Internet of Things.

GPS: Global Positioning System.

# List of Symbols

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## List of Symbols

$\epsilon_0$ : Electrical permittivity of vacuum.

$\epsilon_{eff}$ : Effective permittivity.

$\epsilon_r$ : Relative permittivity.

$\Delta$ : Conductor skin depth.

$\Delta L$ : is the length extension of the patch.

$\omega$ : Pulse.

$Z$ : Input impedance

$Z_0$ : Characteristic impedance.

$Z_{in}$ : Antenna input impedance.

$\omega_r$ : angular resonance frequency.

$\Gamma$ : Reflection coefficient

$C$ : Speed of light in vacuum

$U$ : Radiation intensity

$Q_c$ : Radiation quality factor.

$W$ : Patch width.

## General Introduction

The rapid development of new technologies has transformed the field of telecommunications, leading to an increased demand for efficient and integrated communication systems. In this context, antennas play an essential role in both civilian and military applications. Researchers are constantly striving to develop antennas with high performance, small size, and easy integration into electronic devices.

Among miniaturised antennas, patch antennas, also known as printed antennas or microstrip antennas, stand out for their simplicity, light weight, low cost and ease of fabrication. These antennas have gained widespread popularity because they can be easily integrated with printed circuits and can work efficiently in modern communication systems, especially in high frequency applications such as: Wi-Fi, 5G, Internet of Things (IoT), and satellite communications.

This study aims to design, model, and simulate the performance of patch antennas using HFSS (High Frequency Structures Simulator) software, by studying the effect of antenna shape and feeding method on its electromagnetic properties. The focus will be on analysing several parameters such as S11 reflection coefficient, radiation pattern, bandwidth, and VSWR at 2.4 GHz.

To achieve this goal, the work has been divided into three chapters:

Chapter I: Basic concepts related to antenna theory, types, characteristics, and general applications.

Chapter II: This chapter is devoted to an in-depth study of patch antennas, including their working principle, different geometries, feeding techniques, and their advantages and disadvantages.

Chapter 3: Design and simulation of conventional and modified patch antennas using HFSS software, analysing and comparing the results obtained in terms of performance.

*CHAPTER I*

**Antenna Theory**

**“Antennas are the eyes and ears of wireless systems”**

Constantine A.Balanis

**Chapter summary**

For wireless systems, the antenna is one of the critical components. A good design of the antenna can relax system requirements and improve overall system performance. The wireless systems include a large variety of different kinds, such as radar, navigation, landing systems, direct broadcast TV, satellite communications, mobile communications and so on. An antenna could be as large as 100m by 100m for radio telescope or as small as the order of centimeters in built-in handsets. All of them play an important role in science and daily life. Today we enjoy much benefit from wireless, and the significant contributions of antennas should not be underestimated. This chapter is concerned with the study of antennas as an essential element in wireless communication systems, as they play a pivotal role in transmitting and receiving electromagnetic waves. The chapter deals with the definition and function of an antenna in general, along with the classification of antennas and their basic characteristics such as radiation pattern, gain, directivity, and bandwidth. The most important practical applications of antennas in different fields of communication are also discussed. The chapter also includes key concepts related to antenna performance, such as radiation patterns and signal quality. The main types of antennas, such as wire antennas, reflector antennas, and array antennas, are reviewed, with a special focus on Patch Antennas due to their importance in modern applications. The chapter concludes with a review of different antenna feeding techniques.

**I.1. Introduction:**

Antennas and antenna systems are the building blocks of wireless communication networks, which have grown rapidly thanks to advances in antenna technology. No wireless system, no matter how complex, can function efficiently without antennas capable of sending and receiving the electromagnetic waves that carry data and information. This is similar to how humans rely heavily on their sense of sight and hearing to communicate with the world around them.

With the development of wireless communication technologies, the proliferation and use of wireless devices has increased dramatically, as all modern communication systems rely on antennas to transmit and receive data via electromagnetic waves. For this reason, antennas have become an indispensable element in enabling wireless connectivity and meeting the growing demand for communication services in various fields

## I.2. Definition and Function of an Antenna

### I.2.1. Definition and Function of an Antenna

An antenna is an electromagnetic radiator that transmits and/or receives electromagnetic energy. This energy can exist in the form of light waves, radio waves, cell phone signals, or radar signals. It creates an electromagnetic field that travels from the transmitting antenna to the receiving antenna, which then converts the electromagnetic wave into electrical signals that are applied to the receiver's input stages. The type of energy we want to send or receive depends on the application. Antennas are designed for specific applications. There are many different types of antennas: They can be very small or very large, and their designs can vary greatly from simple to complex. For example, in a radar system we want to track only targets of interest, and a microwave oven radiates energy towards specific targets (food) within an enclosed space (oven)[3][4].

### I.2.2. Classification of Antennas

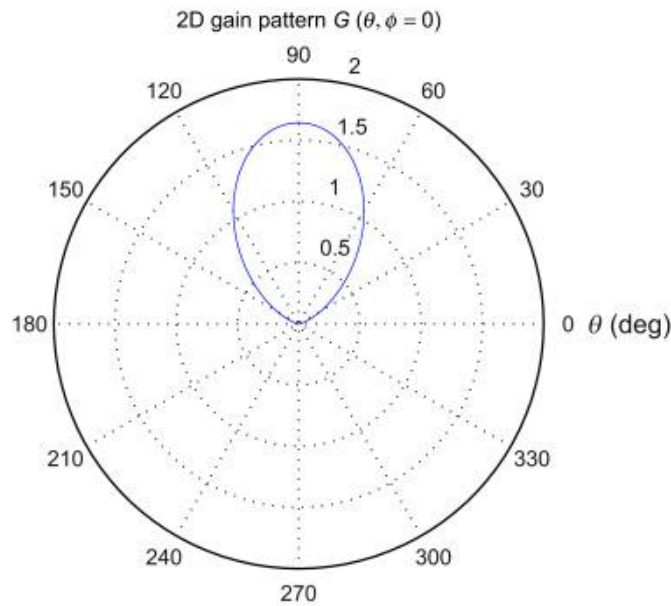
Antennas can be classified based on several criteria, each reflecting a specific property or application. Below are the main classification methods: [16][17][25][26][27]

Classification Criterion	Type	Examples
Physical Structure	Dipole Antennas	"Rabbit ears" antennas
	Monopole Antennas	Telescopic antennas
	Loop Antennas	Small metal loops
	Composite Antennas	Biconical antennas
Directionality	Omnidirectional Antennas	Dipole antennas
	Directional Antennas	Yagi antennas, Helical antennas
	Semi-Directional Antennas	Street antennas
Polarization	Linear Polarization	Most conventional antennas
	Circular Polarization	Helical antennas
Frequency Band	Narrowband Antennas	Traditional dipole antennas
	Broadband Antennas	Biconical antennas
Application	Wireless Communications	Mobile Phone Antenna
	Radio and TV Broadcasting	TV broadcast antennas
	Radar	Radar antennas
	Satellite Communications	Satellite dish antennas

### I.2.3. Fundamental Concepts of Antennas

### I.2.3.1. Radiation Pattern

The radiation pattern is defined as a mathematical function or a graphical representation of the far field (ie, for  $r \gg 2D^2/\lambda$ , with  $D$  being the largest dimension of the antenna) radiation properties of the antenna, as a function of the direction of departure of the electromagnetic (EM) wave. A radiation pattern can represent several quantities, such as gain, directivity, electric field, or radiation vector. Consequently, the terms gain pattern, electric field pattern, or radiation vector pattern are used, respectively[10].



*Figure I.1 . Vertical cut of the 3D gain pattern of a half-wavelength vertical dipole in free space (for  $\phi = 0$  degree)[10].*

### I.2.3.2. Power Density

The power density is the rate of flow of electromagnetic energy per unit area used to measure the amount of radiation at a given point from a transmitting antenna. This quantity is expressed in units of watts per square meter ( $\text{W}/\text{m}^2$ ) or milli-watts per square cm ( $\text{mW}/\text{cm}^2$ ). The power density ( $P_d$ ) of the equivalent plane wave is generally expressed as [11]:

$$P_d = \frac{1}{2} \cdot \text{Re}[\vec{E} \times \vec{H}] \quad (\text{I.1})$$

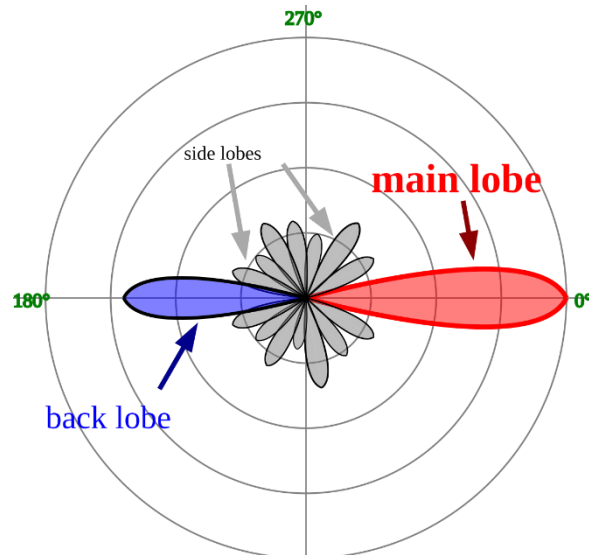
$$P_d = \frac{|E_{rms}|^2}{Z_0} = Z_0 \cdot |H_{rms}|^2 \quad (\text{I.2})$$

#### Where

$E$  and  $H$  are the electric and magnetic fields intensity of the electromagnetic waves,  $Z_0$  is the impedance of the free space.

### I.2.3.3. Directivity (D)

Directivity is a fundamental antenna parameter. It is a measure of how 'directional' an antenna's radiation pattern is. An antenna that radiates equally in all directions would have effectively zero directionality, and the directivity of this type of antenna would be 1 (or 0 dB)[12].

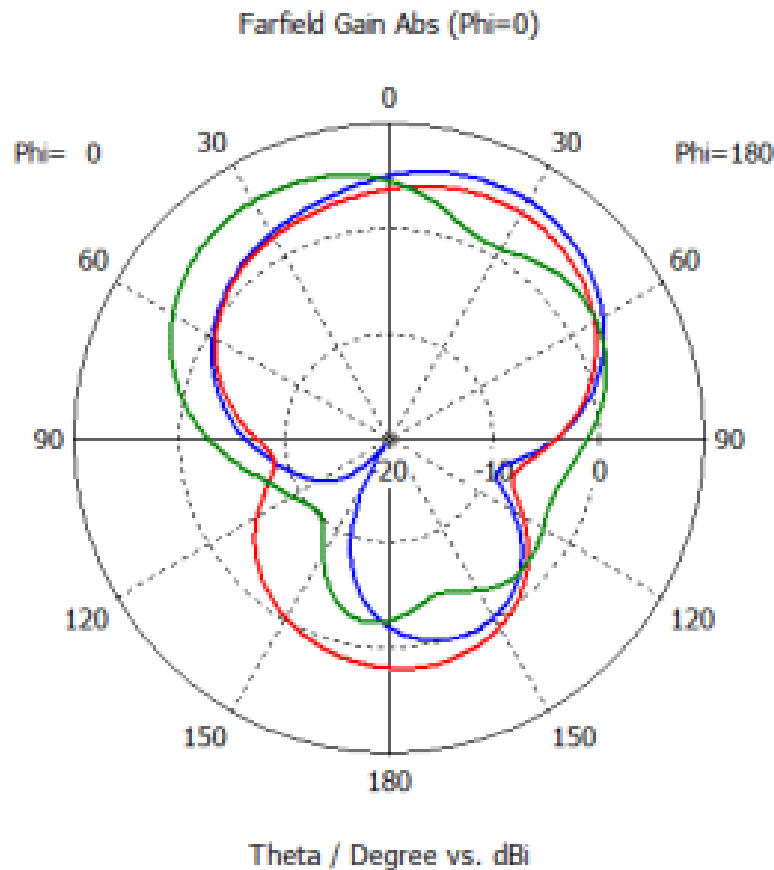


*Figure I.2 . Diagram showing directivity: the highest power density of this antenna is in the direction of the red lobe [14].*

### I.2.3.4. Gain (G)

In electromagnetics, an antenna's power gain or simply gain is a key performance number that combines the antenna's directivity and electrical efficiency. As a transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction. As a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power.

When no direction is specified, "gain" refers to the peak value of the gain. The radiation pattern is a plot of the gain as a function of direction [13].



*Figure I.3 : Antenna Gain plot for  $\phi = 0^\circ$  and  $\phi = 90^\circ$  at 2.4 GHz [15].*

### I.2.3.5. Efficiency

Antenna Efficiency is the ratio of power radiated (Prad) by the antenna to the power supplied (Ps) to the antenna. The efficiency of an antenna is usually measured in an anechoic chamber where an antenna is fed with some power and the strength of the radiated electromagnetic field in the surrounding space is measured.

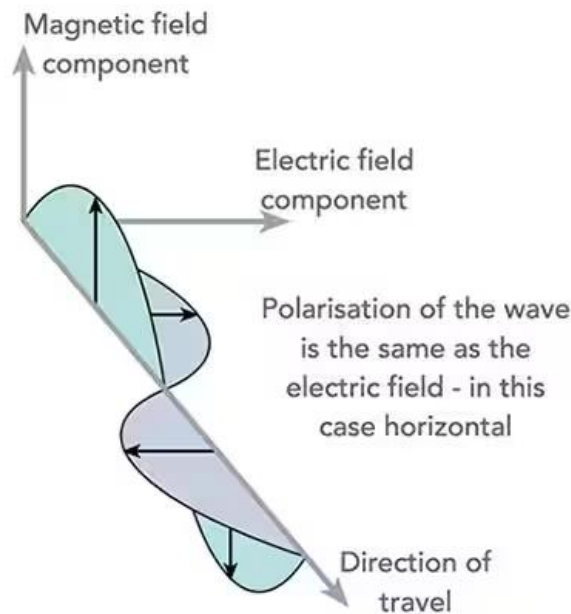
An ideal antenna has 100% antenna efficiency i.e., it transmits all the power fed to it. But in the real world, a good antenna radiates only 50 to 60% of power supplied to it [16].

### I.2.3.6. Polarisation

Antenna polarisation is an important factor when designing and erecting radio antennas or even incorporating them into small wireless or mobile communications systems. Some antennas are vertically polarised, others horizontal, and yet other antenna types have different forms of polarisation.

When designing an antenna, deciding on a particular form of antenna, it is important to understand which way it needs to be polarised. Radio antennas with a particular polarisation will not be effective receiving electromagnetic wave signals with a different polarisation.

That said, many wireless and mobile phone systems may rely on the fact that there are likely to be many reflections between the transmitter and the receiver and these will tend to mean that a signal will have a particular polarisation when it reaches the receiver. Nevertheless, the polarisation of the antenna is still important [5].



*Figure I.4: Electromagnetic energy waves consist of mutually perpendicular E and H field components [5].*

**I.2.3.7. Bandwidth**

Bandwidth is another fundamental antenna parameter. Bandwidth describes the range of frequencies that the antenna can correctly radiate or receive energy. Typically, the required bandwidth is one of the parameters used to select the antenna type. For example, there are many types of antennas with very small bandwidths. These antennas cannot be used in broadband applications [18].

Antenna	Center Frequency	Frequency Range	Fractional Bandwidth	Ratio	Percentage Bandwidth
Patch	1000 MHz	985-1015 MHz	0.03	1.0305:1	3%
Dipole	1000 MHz	960-1040 MHz	0.08	1.083:1	8%
<a href="http://www.antenna-theory.com">www.antenna-theory.com</a>					
Horn	1000 MHz	154-1848 MHz	1.694	12:1	169.40%
Spiral	1000 MHz	95-1900 MHz	1.805	20:1	180.50%

**Table I.1**The Bandwidth for Several Common Antennas [19].

**I.2.3.8. Input Impedance**

An antenna's input impedance refers to the amount of opposition mounted against the flow of current through its conductive material. To remain efficient, an antenna must have an input impedance well balanced to its input transmission line.

**I.2.3.9. Effective Length**

The effective length of an imaginary linear antenna is its total length through which a uniformly distributed current is flowing.

**I.2.3.10. Effective Aperture**

This term is used to describe a receiving antenna. The effective area is a measure of an antenna's ability to extract relevant signals from electromagnetic waves.

**I.2.3.11. Intensity of radiation**

The intensity of radiation of a given antenna refers to the power per unit angle measured in Watts per steradian (W/Sr) [6].

**I.2.3.12. Quality Factor**

The Q factor of the antenna is defined as the quotient between the power stored in the reactive field and the radiated power. The Q factor is commonly used to get an estimate of the bandwidth of an antenna. Since, there is an extensive literature on the Q factor for antennas, see e.g[1].

$$Q = \frac{\omega \max(W_M, W_E)}{P} \quad (I.3)$$

where :

- $\omega$  : is the angular frequency.
- **WM**: the stored magnetic energy, **WE** the stored electric energy.
- **P** : the dissipated power.
- At the resonance frequency,  $\omega_0$ , there are equal amounts of stored electric energy and stored magnetic energy, i.e., **WE = WM**.

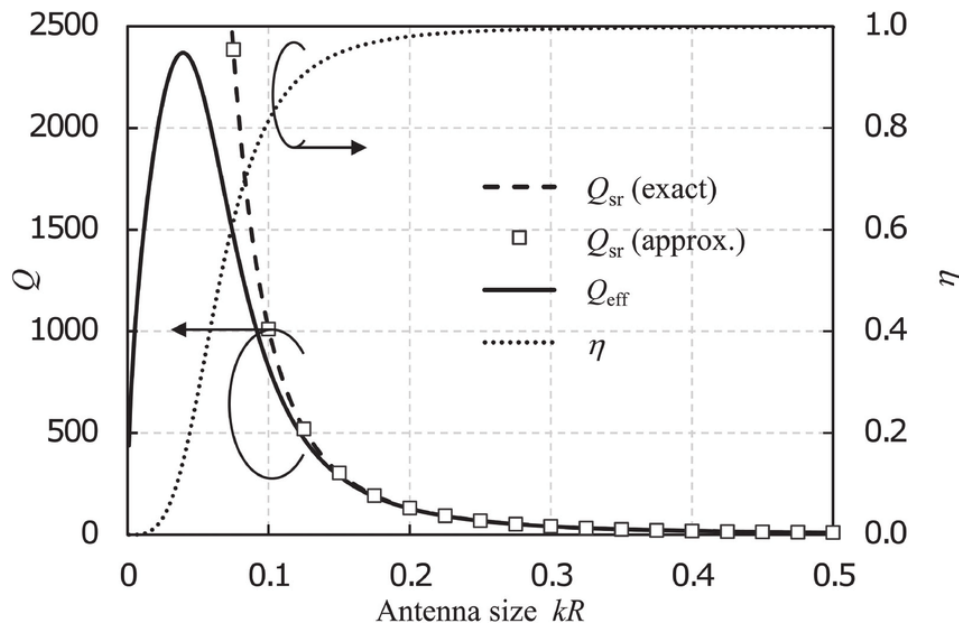


Figure I.5: Showing Effective  $Q$  factor  $Q_{eff}$  and radiation efficiency  $\eta$  [2].

### I.3.Applications of Antennas in Communication

Antennas are fundamental components in any wireless communication system. They serve as the interface between electrical signals and electromagnetic waves, enabling the transmission and reception of data through the air. Their design and functionality vary greatly depending on the application [20][21][22][23][24].

#### 1-Wireless Communication Systems

- Cellular Networks (2G–6G): Antennas used include Omni, Sector, Smart Antennas (MIMO, beamforming). Application: Transmit/receive signals between mobile users and base stations. Example: 5G Massive MIMO antenna arrays for spatial multiplexing.
- Wi-Fi (WLAN 802.11x): Antennas used include Dipole, Patch, Yagi. Application: Provide wireless internet access in homes/offices. Example: 2.4 GHz and 5 GHz antennas in home routers.

#### 2-Satellite Communications

- Types of antennas: Parabolic Dish, Horn, Helical. Applications: Earth-to-satellite and satellite-to-earth links, GPS, TV broadcasting, satellite phones, weather monitoring. Example: High-gain directional antennas used in VSAT terminals.

#### 3-Radio and Television Broadcasting

AM/FM Radio & TV Transmission: Antennas used include Monopole, Mast radiators, Log-periodic antennas. Application: Broadcasting audio/video signals over large areas. Example: 100+ meter-high broadcast towers with high-gain antennas.

**4-Military and Defense Communication**

Tactical & Secure Communications: Antennas used include Wideband whip, SATCOM-on-the-move, phased arrays. Application: Battlefield communications, jamming, missile guidance. Example: AESA (Active Electronically Scanned Arrays) in fighter jets.

**5-Automotive and Vehicular Communication**

Applications: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), Navigation (GPS), infotainment, telematics. Antennas used: Roof-mounted shark fin antennas, patch GPS antennas.

**6-Aerospace and Avionics**

Applications: Aircraft communication (VHF/UHF), radar, ADS-B systems. Antennas used: Flush-mounted patch, blade antennas. Example: Radar altimeters and weather radar on aircraft.

**7-Iot and Smart Devices**

Applications: Smart homes, wearable tech, industrial sensors. Antennas used: Embedded chip antennas, PCB trace antennas. Example: BLE antennas in smartwatches and home automation nodes.

**8-Smart Cities and Public Infrastructure**

Applications: Traffic control, surveillance, public Wi-Fi, environmental monitoring. Antennas used: Directional panel antennas, omnidirectional base stations. Example: 5G street-pole antennas in urban environments.

**9-Emergency and Disaster Recovery Systems**

Applications: Rapid deployment of communication infrastructure (e.g., drone relays, satellite links). Antennas used: Portable high-gain dish antennas, inflatable antennas. Example: Deployable communication kits in natural disaster zones.

**10-Scientific and Deep-Space Communication**

Applications: Space missions, radio astronomy, cosmic background observation. Antennas used: High-precision parabolic reflectors (e.g., DSN). Example: NASA's Deep Space Network communicating with Mars rovers.

## **I.4.Types of Antennas**

### **I.4.1.Wire Antenna**

A wire antenna is an antenna that is made of a conductive wire. Wire antennas can come in different configurations and some of these configurations are dipoles, helix, and loop. Wire antennas can be seen everywhere in daily lives. Some examples of wire antennas are on automobiles as radio antennas, and on buildings as transmitting or receiving antennas [7].

### **I.4.2.Reflector Antenna**

Reflector antennas redirect electromagnetics and refocus it in a certain direction. This type of antenna is commonly used for space crafts for long distance communication . Several common types of reflector antennas are the plane reflector, the corner reflector, and the parabolic reflector. A plane reflector is flat reflector made of a conductor. The electromagnetic waves redirects concept can be compared to sunlight hitting a mirror. A corner reflector usually consists of two plane reflectors joined together at an angle. Typically these two plane reflector joins together to form a 90 degree angle. Figure 16 shows the concept of a 90 degree corner reflector [7].

### **I.4.3.ArrayAntenna**

Array Antenna is a set of multiple connected antennas which work together as a single antenna, to transmit or receive radiowaves. The individual antennas (called elements) are usually connected to a single receiver or transmitter by feedlines that feed the power to the elements in a specific phase relationship. The radio waves radiated by each individual antenna combine and superpose, adding together (interfering constructively) to enhance the power radiated in desired directions, and cancelling (interfering destructively) to reduce the power radiated in other directions[9].

### **I.4.4.Microstrip**

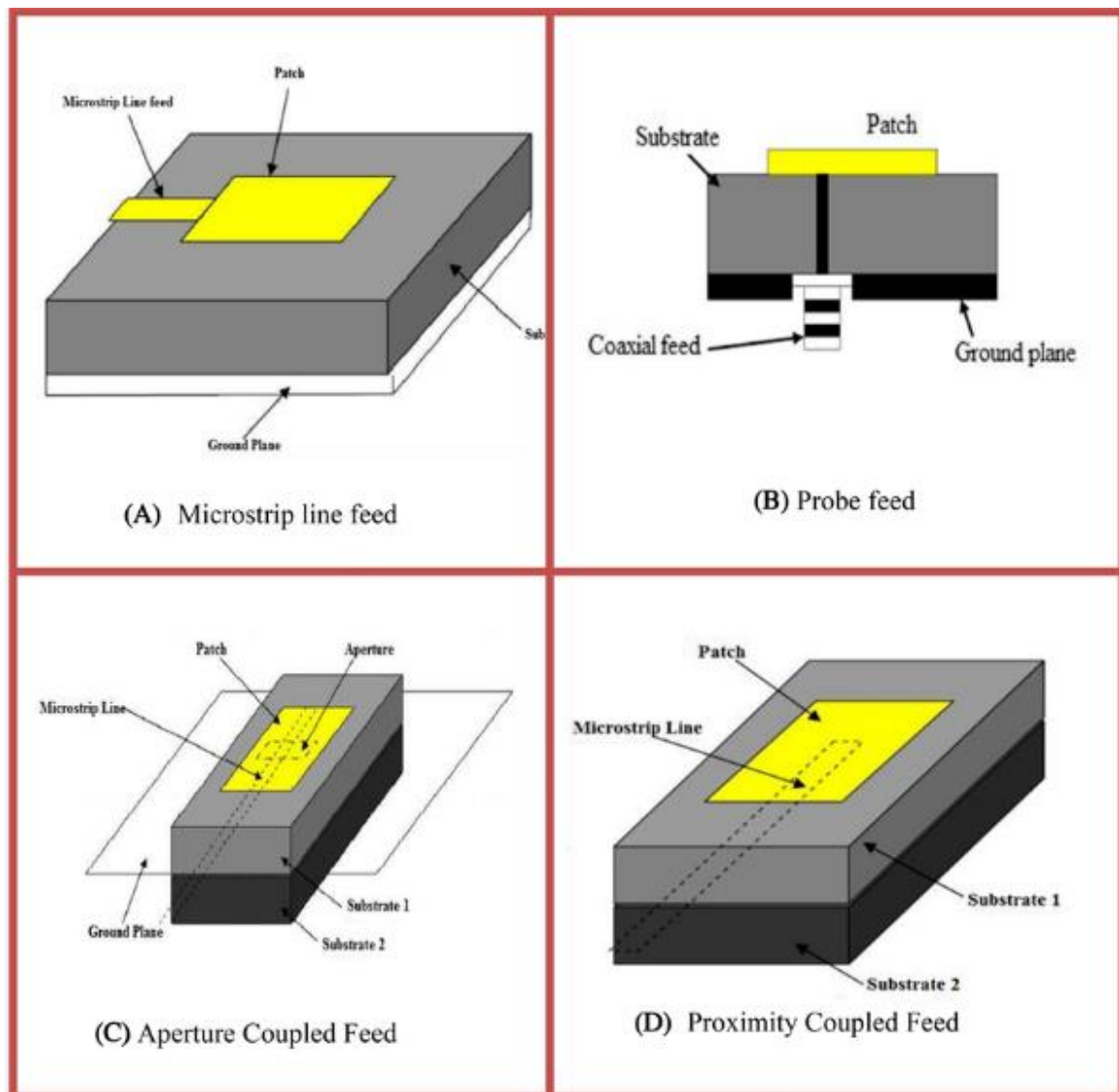
### **Antenna**

A microstrip antenna (also known as a printed antenna) usually means an antenna fabricated using microstrip techniques on a printed circuit board (PCB).It is a kind of internal antenna. They are mostly used at microwave frequencies. An individual microstrip antenna consists of a patch of metal foil of various shapes (a patch antenna) on the surface of a PCB (printed circuit board), with a metal foil ground plane on the other side of the board[8].

### I.5. Feeding Techniques

A feedline is used to excite to radiate by direct or indirect contact. There are many different techniques of feeding and four most popular techniques are coaxial probe feed, microstrip line, aperture coupling and proximity coupling.

- **Coaxial probe feeding** is feeding method in which that the inner conductor of the coaxial is attached to the radiation patch of the antenna while the outer conductor is connected to the ground plane. Advantages of coaxial feeding is easy of fabrication, easy to match, low spurious radiation and its disadvantages is narrow bandwidth, Difficult to model specially for thick substrate.
- **Microstrip line feed** is one of the easier methods to fabricate as it is a just conducting strip connecting to the patch and therefore can be consider as extension of patch. It is simple to model and easy to match by controlling the inset position. However the disadvantage of this method is that as substrate thickness increases surface wave and spurious feed radiation increases which limit the bandwidth.
- **Aperture coupled feed** consist of two different substrate separated by a ground plane. On the bottom side of lower substrate there is a microstrip feed line whose energy is coupled to the patch through a slot on the ground plane separating two substrates. This arrangement allows independent optimization of the feed mechanism and the radiating element. Normally top substrate uses a thick low dielectric constant substrate while for the bottom substrate; it is the high dielectric substrate. The ground plane, which is in the middle, isolates the feed from radiation element and minimizes interference of spurious radiation for pattern formation and polarization purity. Advantages is allows independent optimization of feed mechanism element.
- **Proximity coupling** has the largest bandwidth, has low spurious radiation. However fabrication is difficult. Length of feeding stub and width-to-length ratio of patch is used to control the match. Its coupling mechanism is capacitive in nature. The major disadvantage of this feeding technique is that it is difficult to fabricate because of the two dielectric layers that need proper alignment. Also there is increase in overall thickness of the antenna [28].



*Figure I.6: Showing 4 feeding Methods for Microstrip Antenna [29].*

## I.6.Conclusion

In this chapter, we reviewed the basic principles associated with antennas, including their definition, functions, and different types. Some important characteristics that determine the performance of an antenna have also been touched upon, providing a necessary theoretical foundation for the following chapters.

## *CHAPTER II*

# **Patch Antenna**

**Chapter summary**

In the rapidly evolving landscape of wireless communication, patch antennas have emerged as a cornerstone technology due to their compact design, planar structure, and efficient performance in high-frequency bands. These antennas also referred to as Microstrip antennas have become indispensable in modern applications ranging from smartphones and wearable devices to satellite systems and 5G infrastructure.

This chapter delves into the fundamentals, design principles, and performance characteristics of patch antennas. Starting with an overview of their basic structure and operational advantages, it explores their theoretical foundations, diverse geometrical variations, and the critical factors influencing their efficiency and bandwidth. Furthermore, it presents modern design and simulation techniques, evaluates their radiation behaviour and compares them with traditional antenna types.

The chapter concludes by addressing the current challenges associated with patch antenna technology, such as limited bandwidth and susceptibility to surface wave losses, while highlighting emerging trends and research opportunities in fields like millimetre wave 5G systems, IoT networks, and reconfigurable intelligent surfaces (RIS).

Through this comprehensive examination, the chapter aims to equip the reader with a solid understanding of patch antennas, their evolving role in next-generation communication systems, and the design strategies required to optimize their performance

**II.1.Introduction****II.1.1.Overview of Patch Antennas**

Microstrip patch antennas are now essential components in modern wireless communication systems because of their multiple benefits and flexible uses, as well as their small size, lightweight, and effectiveness. These antennas are flat structures, usually made on a dielectric substrate, consisting of a radiating patch on one side and a ground plane on the other. The dielectric substance divides the patch and ground plane, allowing for customization to achieve specific features. These antennas specifically function in several frequency bands, making them ideal for applications such as 5G and IoT. They provide benefits such as significant amplification, an extensive frequency range, and compact dimensions, fulfilling the requirements for enhanced performance across a wide range of frequencies. Microstrip patch antennas are constantly developing to suit the demands of new technologies, including novel elements like slots, parasitic strips, and corporate feed mechanisms to improve performance and efficiency. Due to their adaptability, they are

well- suited for a wide range of applications, including wireless sensor networks and long-range wireless communications in IoT systems[55].

### **II.1.2.Advantages of Patch Antennas**

Microstrip antennas have several advantages compared to conventional micro-wave antennas, and therefore many applications cover the broad frequency range from 100 MHz to 100 GHz [36]. Some of the principal advantages of microstrip antennas compared to conventional microwave antennas are:

- Light weight, low volume, and thin profile configurations, which can be made conformal;
- Low fabrication cost; readily amenable to mass production;
- Linear and circular polarizations are possible with simple feed;
- Dual-frequency and dual-polarization antennas can be easily made;
- No cavity backing is required;
- Can be easily integrated with microwave integrated circuits;
- Feed lines and matching networks can be fabricated simultaneously with the antenna structure.

### **II.1.3.Applications in Modern Communication Systems**

The Microstrip patch antennas are well known for their performance and their robust design, fabrication and their extent usage. The advantages of this Microstrip patch antenna are to overcome their de-merits such as easy to design, light weight...etc [32][33][34][35],some of the applications include;

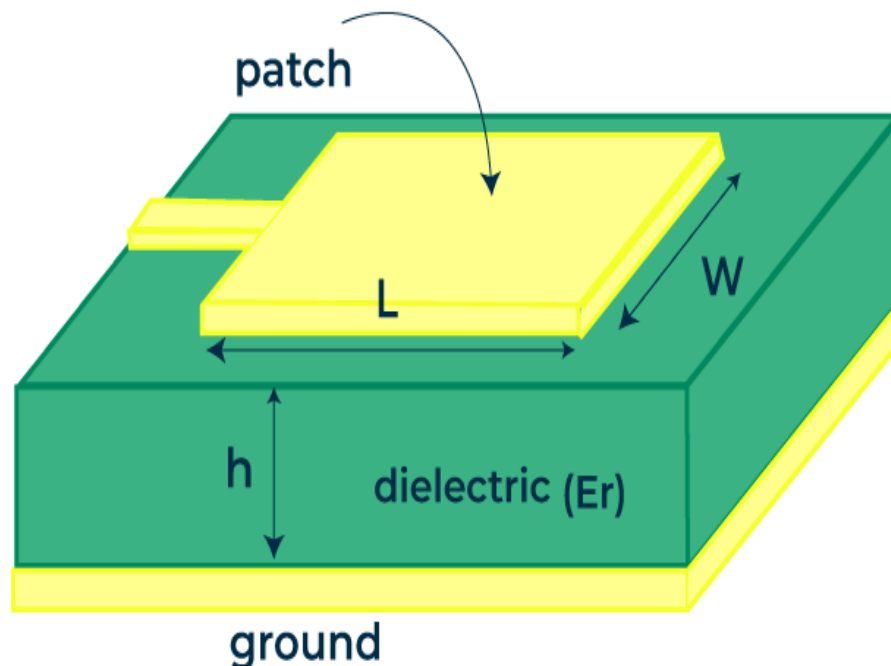
- Enhancing signal focus.
- Minimizing interference.
- Improving efficiency in microwave links, point-to-point backhuls, and modern cellular networks.
- 5G Networks and IoT devices
- WiMAX systems.
- RFID readers.
- Wireless LANs (WLANs).
- Filter– Antenna Integration

## II.2.Patch Antenna Theory

### II.2.1.Definition and Basic Principles

Antenna of Micro-strip patch is the foremost type of printed antenna. It has a major role in wireless communication systems. Fabrication can be easily done using micro strip antenna. Ground plane, substrate and radiating patch are there in a structure of this antenna. Patch dimensions defines radiating feature of antenna. Length and width parameters are used for representing patch [38].

The patch antenna's basic form: a flat plate over a ground plane (usually a PC board). The center conductor of a coax serves as the feed probe to couple electromagnetic energy in and/or out of the patch as showing in Figure II.1. The electric field distribution of a rectangular patch excited in its fundamental mode is also indicated [39].



*Figure II.1: Showing Structure and Dimensions of the Patch Antenna [49].*

### II.2.2.Impact of Geometry on Performance

The geometry of a patch antenna—including its shape, dimensions, and substrate thickness—has a critical influence on its electrical characteristics. The resonant frequency is predominantly determined by the patch length, typically approximating half the wavelength within the dielectric medium. Various geometries, such as rectangular, circular, and

triangular, produce distinct radiation patterns and affect impedance matching and bandwidth. Advanced patch designs, including U-shaped and E-shaped configurations, are often employed to enhance bandwidth. Additionally, increasing the substrate height or reducing the dielectric constant generally improves bandwidth and efficiency, provided impedance matching is maintained to avoid radiation losses [47].

### **II.2.3.Factors Affecting Patch Antenna Performance**

Patch antennas are affected by several key factors that directly affect efficiency, bandwidth, gain, and radiation pattern. Below are the most important of these factors supported by scientific sources [57][58][59]:

#### **1. Substrate material properties:**

- Dielectric constant ( $\epsilon_r$ ): A low dielectric constant increases radiation efficiency and bandwidth, while a high dielectric constant allows the antenna size to be minimized but reduces bandwidth and efficiency.
- Loss Tangent: High increases dielectric losses and decreases efficiency.

#### **2. Substrate Thickness:**

- Increasing the thickness of the substrate often increases bandwidth and improves efficiency, but can also cause excitation of surface waves that reduce efficiency and increase unwanted radiation.

#### **3. Patch Dimensions:**

- Width: It has a significant impact on bandwidth and efficiency, as increasing the width expands the bandwidth.
- Patch Length: Mainly affects the resonant frequency of the antenna.

#### **4. Feeding Technique:**

- The feeding method (e.g. microstrip line, coaxial probe, slot feeding) affects the input impedance, reflection loss, and radiation pattern.

#### **5. Fabrication Accuracy:**

- Any deviation in patch dimensions or feed position may result in performance changes such as reflection loss and bandwidth.

## II.3. Different Patch Antenna Geometries

### II.3.1. Conventional Patch Antenna Geometry

In its fundamental form, a patch antenna comprises a flat radiating element—commonly referred to as a "patch"—that is connected to a metallic transmission line known as the feed line. This configuration is printed on the top surface of a dielectric substrate, while the opposite side is backed by a ground plane.

The geometry of the patch is typically rectangular in conventional designs, though other shapes such as circular, triangular, or annular rings are also employed based on the intended application. This layout is not only compact and lightweight but also highly suitable for integration with planar microwave circuits.

The simplicity of its structure, combined with its low profile and ease of fabrication, makes the rectangular patch antenna a preferred choice in modern communication systems—particularly in WLAN, mobile, satellite, and aerospace applications—where size, cost, and efficiency are critical constraints [47].

### II.3.2. Slot-Loaded Patch Antennas

Slot-Loaded Patch Antennas are a type of patch antennas in which slots or slots of different geometric shapes are inserted into the metal patch to improve performance or add new functionality to the antenna [41][44][45][46][48].

#### **The most important features and benefits of slot loading:**

- **Multi-band:** Inserting slots (e.g. U-slot, E-slot, Y-slot) allows the antenna to operate on more than one resonant frequency, making it suitable for applications such as Wi-Fi, WiMAX, GPS, and dual or tri-band communications.
- **Broaden the bandwidth:** Slots can increase the bandwidth of the antenna compared to traditional antennas, such as in the case of U or E-shaped slots.
- **Miniaturisation:** Introducing notches reduces the resonant frequency of the antenna, allowing smaller antennas to be designed with the same desired frequency, which is important in embedded and wearable devices.
- **Improved gain and efficiency:** Notches can optimise the distribution of the electric field over the patch surface, resulting in higher gain and better radiation efficiency.
- **Improved sensing sensitivity:** In sensing applications, such as measuring the dielectric constant of materials, notches increase the antenna's sensitivity to changes in the environment.
-

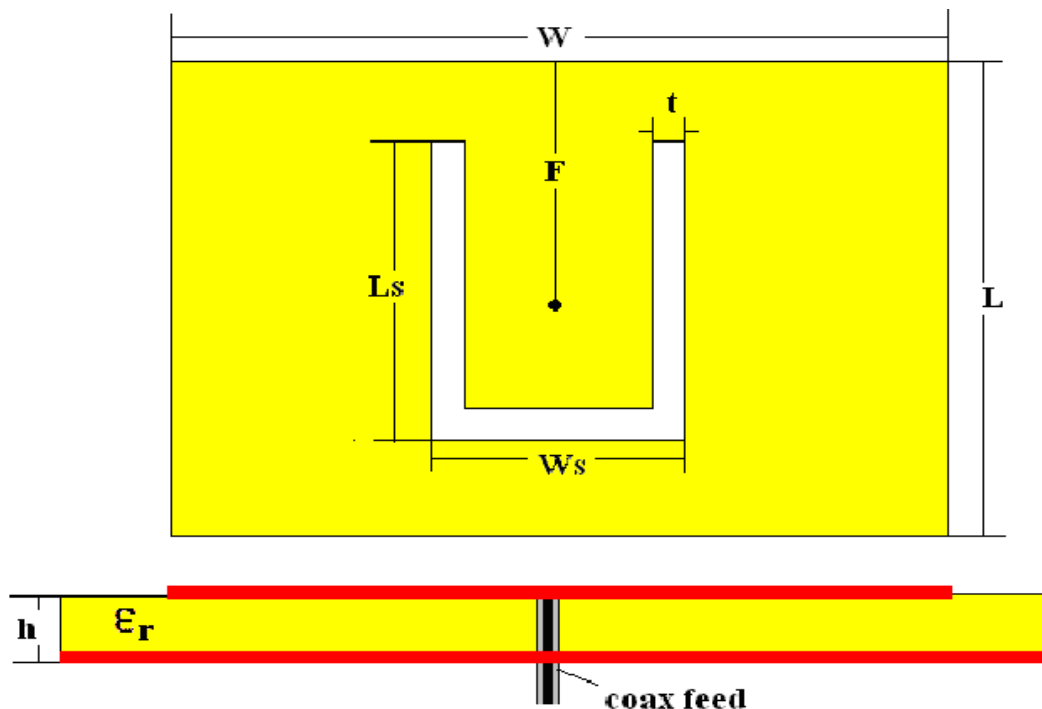
**Examples of applications and designs of slit-loaded patch antennas:**

- Dual or tri-band antennas: By using Y- and U-shaped slots, resonance at multiple frequencies can be achieved to cover different applications.
- Material sensing antennas: Slits are used to increase sensitivity and enable the antenna to act as a standalone sensor for measuring material properties.
- Printed or embroidered antennas: These antennas can be fabricated on flexible substrates or even using embroidery for wearable devices while maintaining high performance.

**Effect of notch dimensions:**

- Increasing the slit width often significantly lowers the resonant frequency of the antenna.
- Slit length has less effect on the resonant frequency, but the effect becomes more pronounced as the slit width increases.

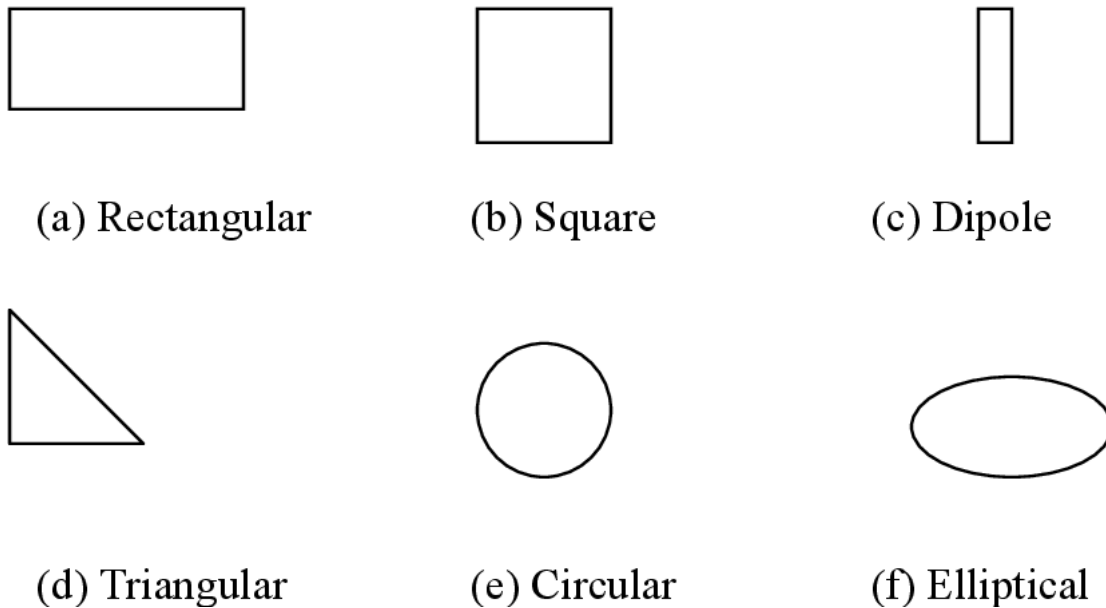
Slot-loaded patch antennas provide effective solutions to meet modern communication requirements in terms of multi-band, miniaturisation, and performance optimisation, with adaptability for diverse applications including wireless communications, sensing, and wearable systems.



*Figure II.2: U Slot Loaded Rectangular Microstrip Antenna [54].*

### II.3.3. Other Shapes Used in Patch Antenna Design

There are a large number of shapes of microstrip patch antennas; they have been designed to match specific characteristics. Some of the common types are shown in figure II.2, for millimeter wave frequencies, the most common types are rectangular, square, and circular patches.



*Figure II.3: Different shapes of microstrip patch elements [50].*

## II.4. Design and Simulation of Patch Antennas

### II.4.1. Design Considerations

The design process of a microstrip patch antenna involves a sequence of processes and techniques with the goal of reaching its established parameters.

The typical process consists of Specification of the frequency range, gain, bandwidth, and other requirements suitable to the planned application. shape Selection and Optimization lies on the appropriate patch shape and size, keeping into consideration the required resonant frequency and bandwidth. Optimization techniques, such as parametric studies and genetic algorithms, improve the design parameters to achieve optimal performance. Substrate Selection depends on Choosing a suitable dielectric substrate according to the specified dielectric constant, loss tangent, and thermal characteristics .To design Feed Mechanism it

must be Determined the optimal feed type and position for effective power transmission to the patch .

#### II .4.2. Simulation Tools and Techniques

For running simulation and Analysis, it has to Apply simulation techniques to evaluate the antenna's performance, focusing on its radiation pattern, return loss, bandwidth, and impedance matching Simulation software such as CST Microwave Studio, HFSS , and MATLAB help in the modeling and analysis of antenna properties .Microstrip patch antenna provide multiple advantages, but there are still major challenges that remain in their development and implementation. The challenges are establishing a wide frequency range or bandwidth, minimizing losses, maintaining the quality of polarization, and handling the complexity of production[40].

In this work, Micro-strip patch antenna is designed and simulate on resonant frequency of 2.4 GHz by using HFSS simulating tool. Simulation is performed to obtain the higher bandwidth by varying patch width, patch length and air gap of micro-strips .

#### II.4.3.Comparison with Traditional Antennas

The fundamental differences between Microstrip Patch Antennas and traditional antennas such as Rod Antennas or Dipole Antennas can be summarized in the following table[51][52][53]:

Feature	Patch Antennas	Traditional Antennas
Size	Very compact, flat, suitable for integrated and space-constrained devices	Larger size, requires more installation space
Cost	Low cost, easy mass production using PCB fabrication techniques	Higher manufacturing and installation costs
Gain	Moderate to low gain due to small size (typically lower than traditional antennas)	Higher gain, suitable for long-range communications
Interference resistance	More sensitive to environmental factors and ambient electromagnetic interference	Relatively better resistance to environmental interference

## II.5. Performance Analysis of Patch Antennas

### II.5.1. Bandwidth and Frequency Resonant

- **Bandwidth**

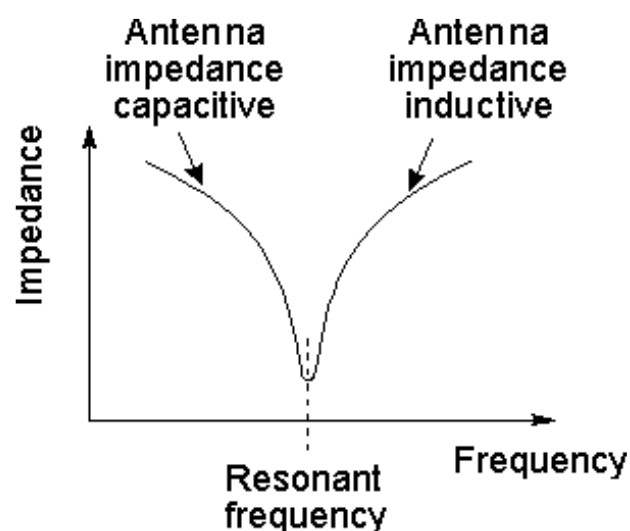
An antenna's bandwidth specifies the range of frequencies over which its performance does not suffer due to a poor impedance matching .

RF antennas are designed to operate around the resonant point. An Antenna can be operated efficiently over a limited bandwidth. If the antenna is operated outside its operating bandwidth range and the radio transmitter is not adequately protected then damage may occur.

For receiving purpose, the performance of the antenna is less critical in some respects. It can be operated outside its normal bandwidth without any fear of damage. However, it is important to ensure that the performance of the antenna design is optimum for best reception [42].

- **Frequency Resonant**

Basically an antenna is a form of tuned circuit that constitutes inductance and capacitance. Consequently, it has a resonant frequency. Resonant frequency is a frequency at where the capacitive reactance and inductive reactance cancel-out each other. At this point where reactance cancel-out each other, the RF antenna becomes purely resistive . The resistance is the combination of the loss resistance and the radiation resistance[42].



*Figure II.4 : Impedance of RF Antenna with Frequency [42].*

## II.5.2. Directivity and Gain

- **Directivity**

It is the ratio of radiation intensity in a given direction at where antenna has strongest emission to the radiation intensity averaged over all directions while the average radiation intensity is equal to the total power radiation by an antenna divided by  $4\pi$ . The formula for directivity is given by [42]:

$$D = \frac{U_{\max}}{U_0} = \frac{4\pi U_{\max}}{P_{\text{rad}}} \quad (\text{I.4})$$

- **Gain**

This parameter is used to measure the degree of directivity of radiation pattern of an Antenna. Antenna gain or power gain may be defined as, ‘the ratio of radiation intensity in a given direction to the radiation intensity of an antenna radiated isotropic manners’. Gain is a dimension-less factor related to power and expressed in decibels .

Long range and better signal qualities are the advantages of high gain antennas but preferentially radiate in a particular direction. Low gain antenna has shorter range but the orientation of the antenna is relatively inconsequential. Gain is given as under [42].

$$\text{Gain} = \text{Efficiency} \times \text{Directivity}$$

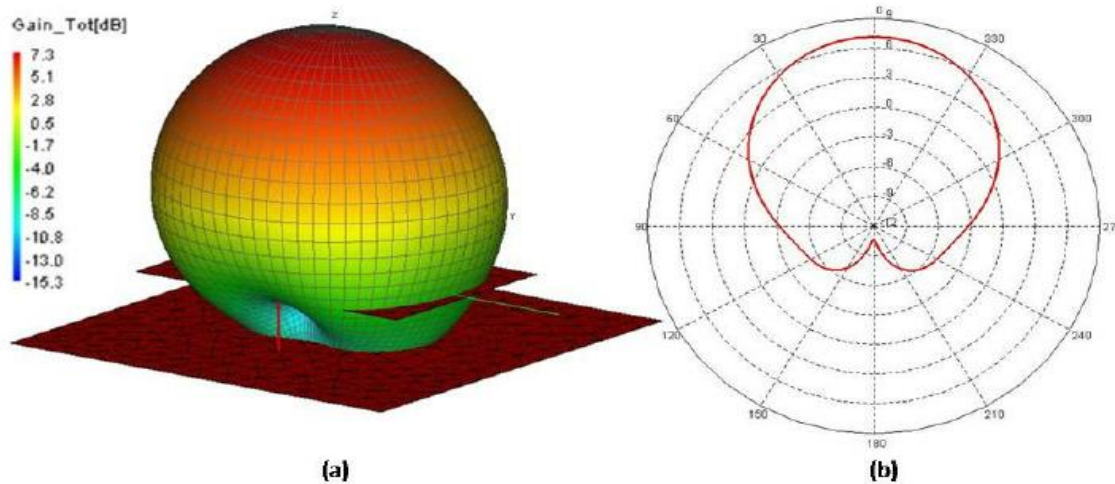


Figure II.5: Rectangular Patch Antenna 3D and 2D Gain [56].

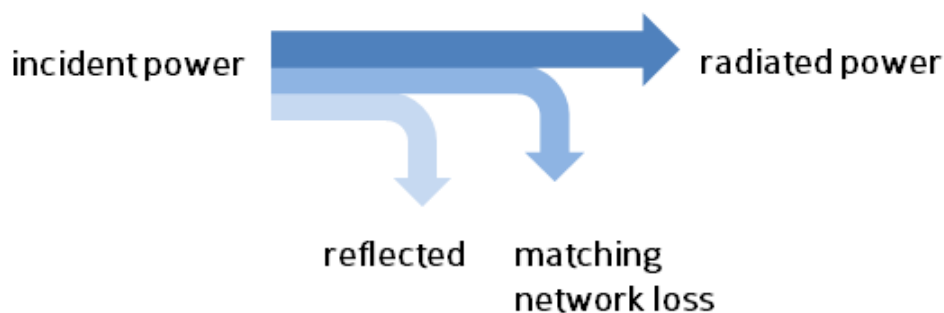
### II.5.3. Radiation Efficiency and VSWR

- **Radiation Efficiency**

Radiation Efficiency is the ability of an antenna that how well an antenna converts accepted power to radiated power. An efficient antenna radiates most of the power received from transmission line. Radiation efficiency is the ratio of Radiation resistance to the sum of radiation resistance and loss resistance. Radiation resistance and loss resistances constitute the resistive part of an antenna. Power transferred from antenna is equalized by the radiation resistance while internal loss of the antenna is incorporated by the loss resistance.

Efficiency = Radiation Resistance / (Radiation Resistance + Loss Resistance)

Radiation Efficiency often expressed as percentage or in dB. For example, an efficiency of 0.8 is 80% or -0.97dB [42].



*Figure II.6: Radiation Efficiency [42].*

- **VSWR**

Voltage Standing Wave Ratio (VSWR) is a measure of numerical description of how much the antenna is matched to transmission line connected to it. It is the ratio between peak amplitude and minimum amplitude of a standing wave along a transmission line.

The reflection coefficient ( $\Gamma$ ) is the ratio of reflected voltage by incident voltage. The relation between Reflection Coefficient and Impedances is ,

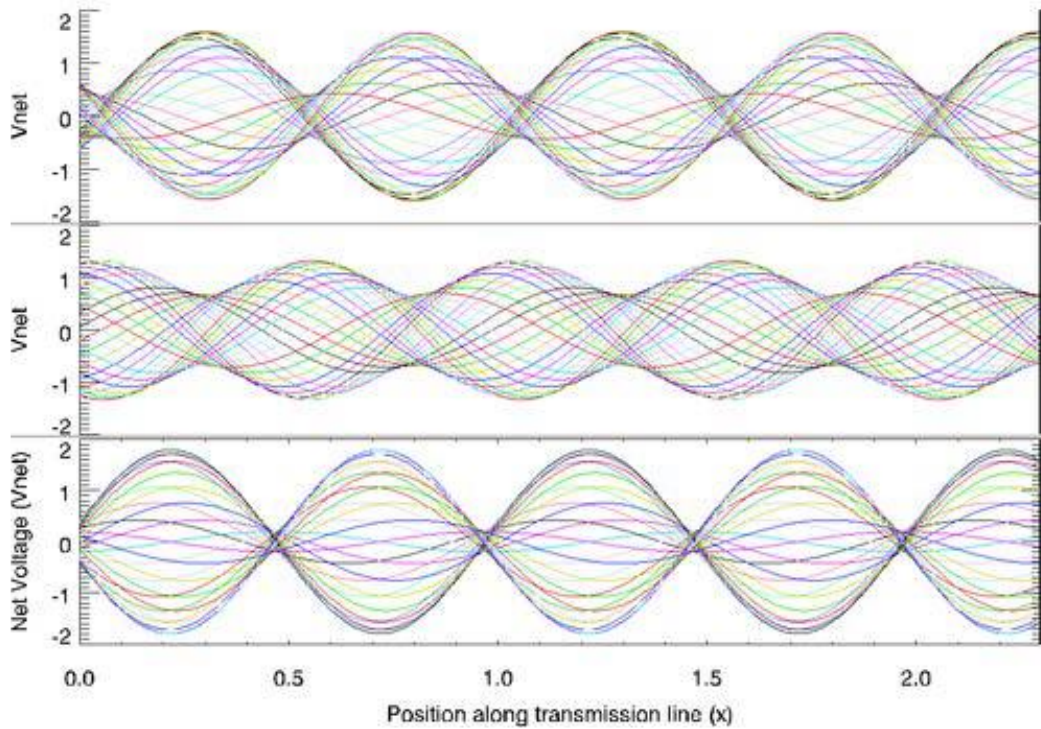
$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} \quad (\text{II.1})$$

Where  $Z_L$  is the load impedance,  $Z_S$  is the source impedance. When load is open circuit means  $Z_L = \text{infinity}$  which lead to  $\Gamma = 1$ . Similarly the when load is short circuited the  $Z_L = 0$

leading to  $\Gamma = -1$ . In case of perfectly matched condition, the load impedance  $Z_L$  is equal to the source impedance so that  $Z_L = Z_s$  which lead to  $\Gamma = 0$ .

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (II.2)$$

In case of perfectly matched antenna,  $\Gamma = 0$ , which lead to  $VSWR = 1$ . Closer the value of  $VSWR$  to 1, more matched the antenna is [42];



*Figure II.7: VSWR [42].*

## II.6.Challenges and Future Trends

### II.6.1 Limitations of Patch Antennas

Microstrip patch antennas have become essential in modern communication systems due to their compact size and ease of fabrication. However, their performance is often constrained by narrow bandwidth, low radiation efficiency, and low gain, especially in miniaturized designs. The performance limits of microstrip patch antennas are helpful in understanding and overcoming these challenges. These performance limits are determined for three key metrics in this thesis, Q-factor (which is inversely proportional to bandwidth), radiation efficiency, and gain. Limits on these metrics provide insights into the maximum achievable performance for these antennas, guiding the design process beyond traditional optimization methods [43].

## II.6.2. Emerging Applications in 5G and Beyond

Recent advancements in patch antenna design have been pivotal for supporting 5G technologies and beyond, focusing on miniaturization, material innovation, and integration with smart components.

### Miniaturization and Performance Enhancement

Introduction of compact, broadband patch antennas using technologies like:

- Ball Grid Array (BGA) packaging
- Metamaterial-based shapes (e.g., circular or pentagonal forms)
- Shorting pins and interdigital feeding.
- Use of Artificial Magnetic Conductor (AMC) surfaces has reduced antenna size by up to 90.6%, improving profile and efficiency.

### Advanced Materials and Manufacturing

- Adoption of additive manufacturing using conductive ABS for 3D-printed antennas.
- Use of air-gap structures for tunable dielectric substrates.
- Radomes made from PTFE and silica have improved protection, gain, and directivity.

### Beamforming Innovations

- Development of self-adaptive beamforming techniques for dynamic applications.
- Materials like ROGERS 3003 enhance gain while reducing array size.
- Beamwidth and gain can be optimized through customized antenna array configurations.

### MIMO System Integration

- Creation of dual-band, dual-polarized antennas with high isolation for 5G MIMO.
- Two-port and multi-slot designs offer omnidirectional coverage and wide bandwidth.
- These antennas are optimized for 5G OFDM standards.

### Integration with RF Modules

- Integration of MEMS switches and bias networks to create multi-frequency switchable antennas.
- RFIC embedding in antenna cavities boosts bandwidth and performance.

- Development of tunable triple-band antennas using U-slots and varactor diodes allows compact, flexible multi-band operation.

These innovations reflect a transformative evolution in patch antenna design—pushing the boundaries of performance, compactness, and adaptability—making them central to 5G, 6G, and future wireless technologies [37].

## **II.7. Conclusion**

This chapter dealt with printed antennas in terms of theoretical and applied principles, where they were introduced and explained their advantages that make them suitable for many modern communication applications, especially in high-frequency wireless systems. The impact of dimensions and geometric shape on antenna performance was also addressed, in addition to the study of various feeding methods. This chapter has helped build an in-depth understanding that can be relied upon in the design and simulation phase, which will be covered in the next chapter.

## *CHAPTER III*

# **Design of rectangular Patch Antenna**

**Chapter summary**

This chapter presents the design and simulation of two types of patch antennas using HFSS software, targeting operation at 2.4 GHz. Initially, a preliminary patch antenna was designed, followed by a modified version aimed at enhancing performance. Simulation results showed that the modified antenna achieved better characteristics in terms of reflection coefficient, bandwidth, and radiation pattern, confirming the effectiveness of geometric modifications in improving the performance of printed antennas.

**III.1.Introduction:**

This chapter aims to explore the various applications of the 2.4 GHz frequency and utilize it in the design of a printed antenna using HFSS software. The focus will be on designing an antenna operating at 2.4 GHz and analyzing its performance characteristics, such as the reflection coefficient  $S_{11}$  and the VSWR specific to this antenna. The 2.4 GHz frequency is widely used in many wireless communication systems, which highlights its importance and justifies its selection for the antenna design in this project.

**III.2. Some Main Technologies that use antennas of 2.4 GHz**

- **WLAN**

(Wireless Local Area Network) is a communication technology that uses radio frequencies to provide internet access and data exchange between devices within a limited geographic area, such as homes or offices, without the need for wires. This technology relies on standards like IEEE 802.11, and its field of operation includes the 2.4 GHz frequency range (2400–2484 MHz), which is primarily used in wireless networks [60].

- **Bluetooth**

Bluetooth is a standard for wireless data exchange over short distances using high-frequency radio waves. It is designed to reduce power consumption and the cost of communication between devices. Bluetooth operates in the Industrial, Scientific, and Medical (ISM) radio band at a frequency of 2.4GHz, specifically from 2.400 to 2.4835 GHz. It uses Frequency Hopping Spread Spectrum (FHSS) technology to minimize interference from other devices operating in the same frequency range [61].

- **Wi-Fi**

It is a standard defined by IEEE 802.11 and is used in Wireless Local Area Networks (WLANs). The 802.11b/g/n versions support data rates ranging from 1 to 54 Mbps, with a range of up to 95 meters outdoors. The 802.11n standard uses double the radio spectrum compared to 802.11a/g, while 802.11a can achieve speeds up to 6 Gbps. Wi-Fi operates in

two main frequency bands: 2.4 GHz (low-band) 5 GHz (high-band) It uses BPSK and QPSK modulation techniques to achieve data rates up to 54 Mbps. The maximum allowed Enhanced Isotropic Radiated Power (EIRP) is 20 dBm (100 mv) [62].

### III.3.HFSS Soft

HFSS (High Frequency Structure Simulator) is a 3D electromagnetic simulation software used for analyzing and designing high-frequency components such as antennas, filters, transmission lines, and microwave devices. Developed by Ansys, the software is based on the Finite Element Method (FEM) to solve Maxwell's equations in the frequency domain.

HFSS provides an integrated environment for 3D geometry design, material property definition, and feed configuration (such as aperture coupling or coaxial feeding). It enables accurate calculation of electromagnetic performance parameters such as return loss (S11),



*LOGO OF ANSYS HFSS SOFTWARE [64].*

antenna gain (Gain), bandwidth (Bandwidth), and radiation patterns (Radiation Patterns). With its high accuracy and user-friendly interface, HFSS is considered an ideal tool for designing precise and advanced antennas [63].

### III.4.Patch Antenna Design Equations - Detailed Explanation

Patch Width (W) :

$$w = \frac{c}{2f} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (III.1)$$

W: Width of the patch (m).

c: Speed of light in free space ( $\approx 3 \times 10^8$  m/s).

f: Resonant frequency (Hz).

$\epsilon_r$ : Relative dielectric constant of the substrate.

The Effective Dielectric Constant ( $\epsilon_{eff}$ ) is given by:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left( \frac{1}{\sqrt{1 + \frac{12h}{w}}} \right) \quad (III.2)$$

$\epsilon_{eff}$ : Effective dielectric constant, considering fringing fields.

h: Height of the substrate (m).

W: Width of the patch (m).

$\epsilon_r$ : Relative dielectric constant.

This formula adjusts the dielectric constant to account for fringing effects that cause the fields to extend beyond the substrate boundary.

The Effective Length ( $L_{eff}$ ) is given by:

$$L_{eff} = \frac{C}{2f\sqrt{\epsilon_{eff}}} \quad (III.3)$$

$L_{eff}$ : Effective length of the patch (m), including fringing field extensions.

f: Resonant frequency (Hz).

$\epsilon_{eff}$ : Effective dielectric constant.

Used to estimate the physical length required for the patch to resonate.

**Length Extension Due to Fringing ( $\Delta L$ ):**

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left( \frac{w}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left( \frac{w}{h} + 0.8 \right)} \quad (III.4)$$

$\Delta L$ : Length extension due to fringing fields (m).

h: Substrate height (m).

W: Width of the patch (m).

$\epsilon_{eff}$ : Effective dielectric constant.

This formula estimates how much longer the patch appears due to the extension of electric fields beyond its edges.

Actual Patch Length (L):

$$L = L_{eff} - 2\Delta L \quad (III.5)$$

L: Actual physical length of the patch (m).

$L_{eff}$ : Effective length (m).

$\Delta L$ : Length extension due to fringing (m).

Gives the actual physical size of the patch, compensating for the fringing effect.

**Actual Patch Length (L):**

$$L = L_{eff} - 2\Delta L \quad (III.6)$$

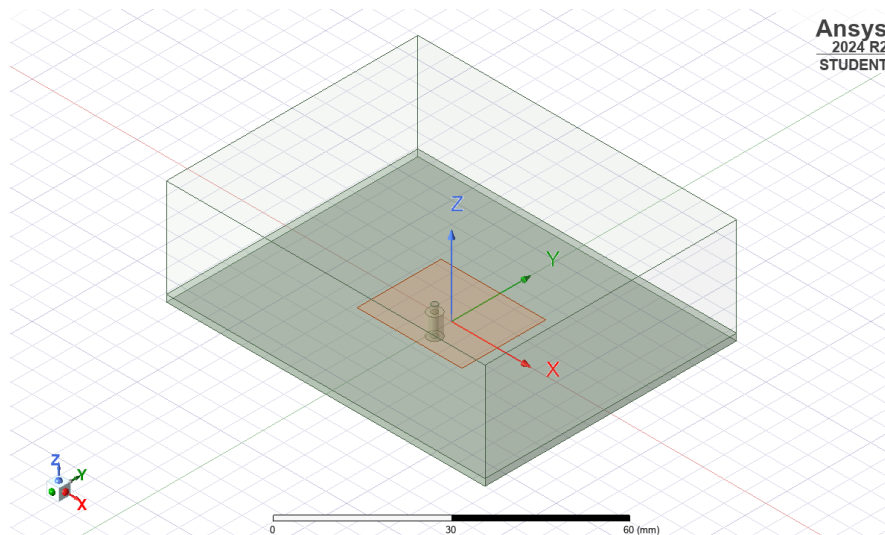
L: Actual physical length of the patch (m).

$L_{eff}$ : Effective length (m).

$\Delta L$ : Length extension due to fringing (m).

Gives the actual physical size of the patch, compensating for the fringing effect [60].

### III.4.1. Initial Antenna



*Figure III.1: Initial antenna image.*

### Initial Patch Antenna design Parameters

Resonant Frequency(fr)	2.4GHz
Patch Length(L)	25mm
Patch width(w)	20mm
Substrate Length(L)	76mm
Substrate width(w)	60mm
Dielectric substrate Height(h)	1.6mm
Relative Permittivity(er)	4.4

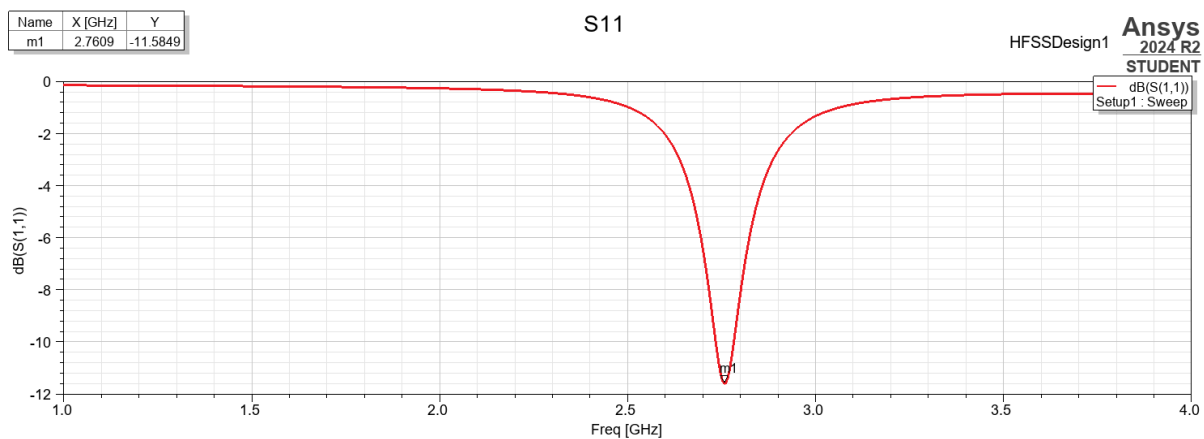
### Explanation and analysis of results

To design an antenna that operates efficiently at 2.4 GHz with a reflection coefficient (S11) lower than -10 dB, an initial design was implemented and simulated to obtain the frequency response curve. This preliminary design plays a key role in evaluating the initial concept of the antenna and verifying the compatibility of its dimensions with theoretical requirements. Through this simulation, the antenna's response and resonant frequency location were observed, and the results showed a shift in the resonant frequency towards 2.6 GHz, deviating from the desired 2.4 GHz.

Moreover, the antenna's performance in terms of S11 was not satisfactory, as the value did not drop below -10 dB at the target frequency. The VSWR curve also showed a clear deviation from the required frequency, as it did not reach the ideal values near 1 at 2.4 GHz, but rather showed a higher value reflecting poor matching and lower transmission and reception efficiency at this frequency.

This indicates that the design does not meet optimal matching conditions, resulting in high reflection and power loss. These findings highlight the importance of the initial design as an exploratory phase that helps identify performance shortcomings and determine the necessary adjustments to the antenna dimensions to achieve resonance and matching at the intended frequency.

#### III.4.1.1. Reflection coefficient S11:



*Figure III.2: Reflection coefficient S11 curve.*

From the VSWR plot, it is observed that the minimum VSWR value (approximately 1.72) occurs at a frequency of 2.7547 GHz, rather than at the target frequency of 2.4

GHz. This indicates that the design has deviated from the desired frequency, suggesting that the antenna or circuit needs to be re-tuned or its dimensions adjusted to achieve optimal matching at 2.4 GHz.

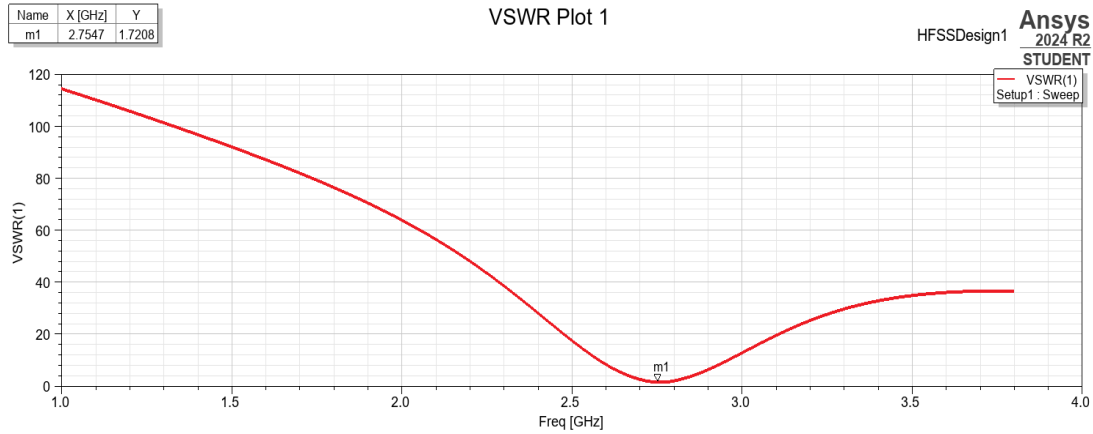


Figure III.3: Voltage standing wave ratio (VSWR) curve .

#### III.4.1.2.3D Gain Plot

The antenna generates upward-directed radiation with a maximum gain of about 0.86 dB, which is relatively low compared to conventional designs, indicating that the radiation performance needs to be improved to obtain higher gain.

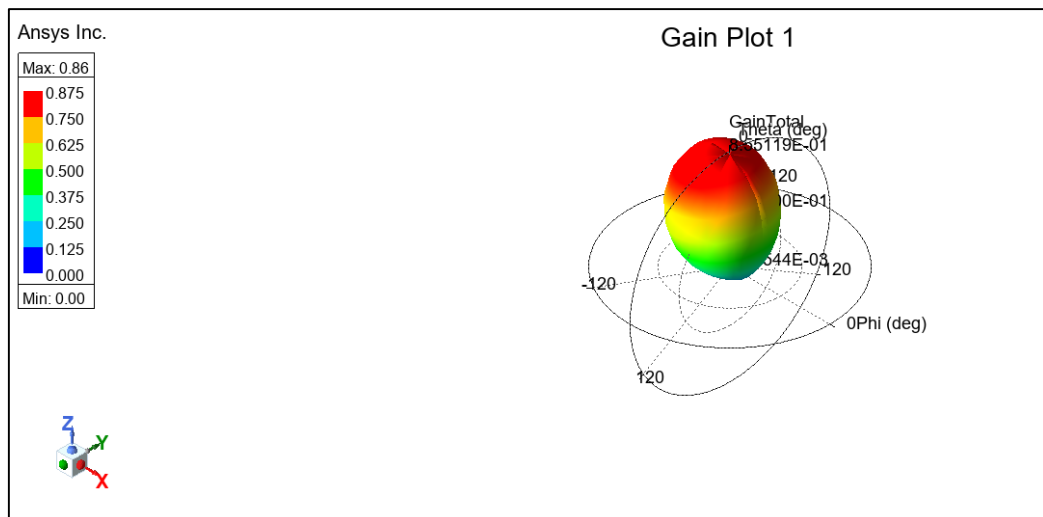


Figure III.4:3D Gain Plot.

### III.4.2.Modified antenna

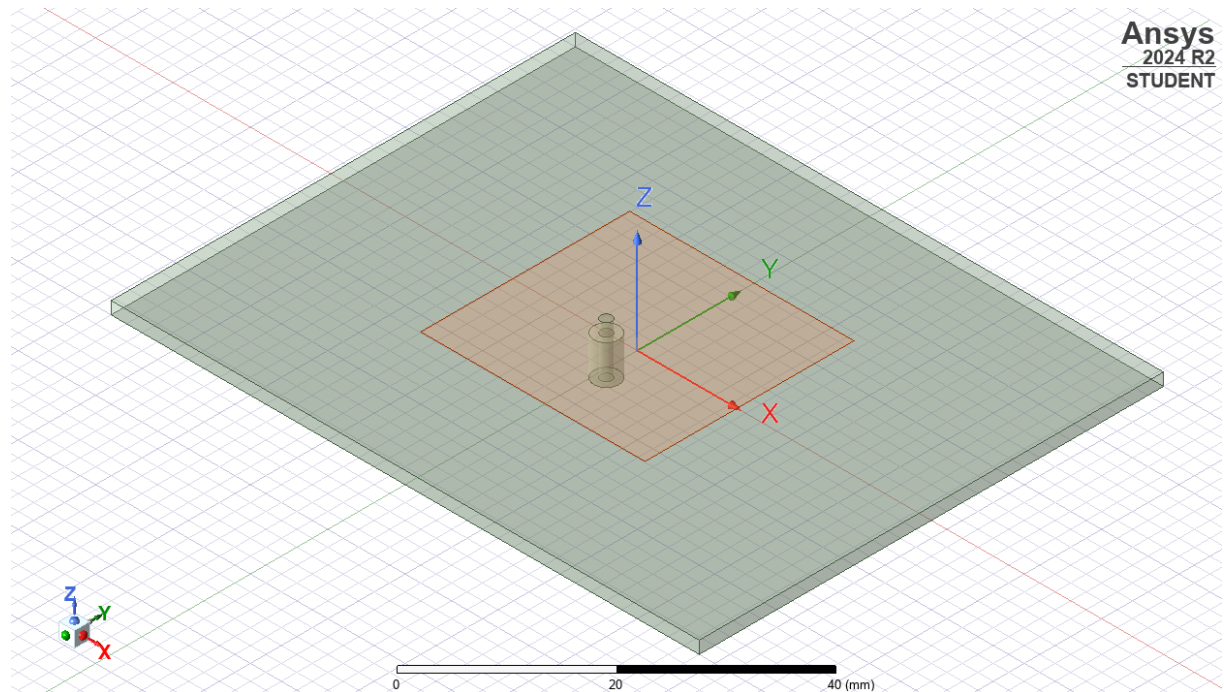


Figure III.5: Modified antenna image .

#### Modified Patch Antenna design Parameters

Resonant Frequency (fr)	2.4 GH
Patch Length(L)	29mm
Patch width(w)	27mm
Dielectric substrate Height(h)	1.6mm
Substrate Length(L)	76mm
Substrate width(w)	60mm
Relative Permittivity(er)	4.4

#### Modified antenna explanation

The antenna consists of three main layers:

1. Ground Plane: A metallic layer placed at the bottom of the antenna, which reflects electromagnetic waves and directs the radiation in the desired direction.

2. Substrate Layer: Positioned between the patch and the ground plane, made of dielectric materials such as FR4 or Rogers. The electrical properties of this layer, such as relative permittivity, directly affect the resonant frequency and the efficiency of the antenna.

3. Radiating Patch: Located at the top, typically in a rectangular or square shape. This patch radiates electromagnetic waves when fed at the appropriate frequency.

In this design, coaxial probe feeding is used, where the inner conductor of a coaxial cable is directly connected to the patch through a small hole in the ground plane. This method is effective in achieving good impedance matching at low to medium frequencies.

This type of antenna is widely used in applications within the 2.4 GHz frequency band, such as Wi-Fi networks and wireless communication systems, due to its simple structure, compact size, and ease of fabrication.

#### III.4.2.1. Reflection coefficient S11 :

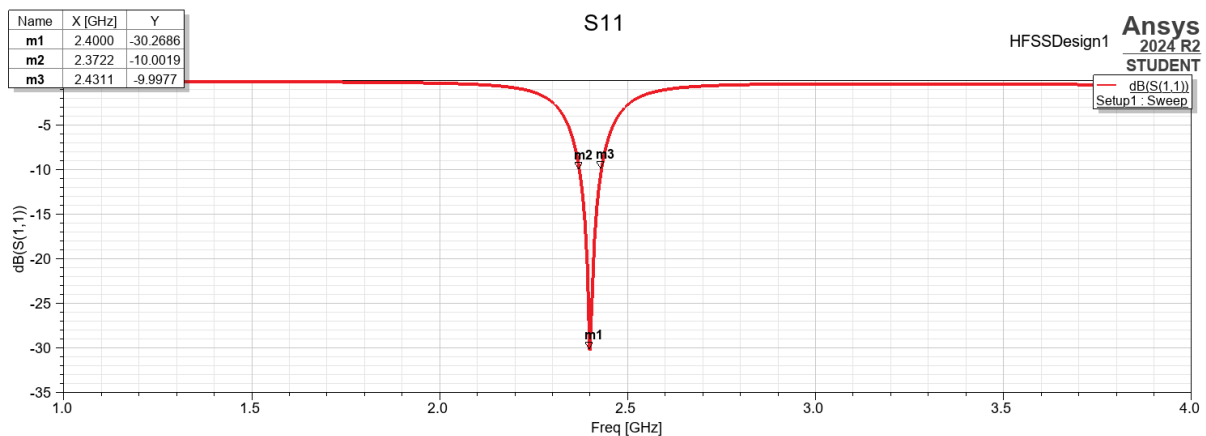


Figure III.6: Reflection coefficient S11 curve.

- **Analysis and interpretation of results**

The figure below shows the S11 (Return Loss) curve in decibels as a function of frequency.

Key Results from the S11 Curve:

Resonant Frequency: The minimum point on the curve occurs at 2.4000 GHz.

S11 Value at Resonance: It reaches -30.2686 dB, which is an excellent value, indicating that less than 0.1% of the transmitted signal is reflected back. This means the antenna operates with high efficiency.

The low S11 value indicates that most of the transmitted power is absorbed or radiated by the antenna, showing good impedance matching between the antenna and the feed line.

bandwidth The bandwidth of an antenna is defined as the frequency range over which the antenna maintains efficient performance, typically where the reflection coefficient  $S_{11} \leq -10$  dB . This indicates that less than 10% of the input power is reflected, ensuring good impedance matching and efficient radiation.

- **According to the updated simulation results:**

Lower frequency limit:

m2: at 2.3722 GHz, where  $S_{11} \approx -10.0019$  dB

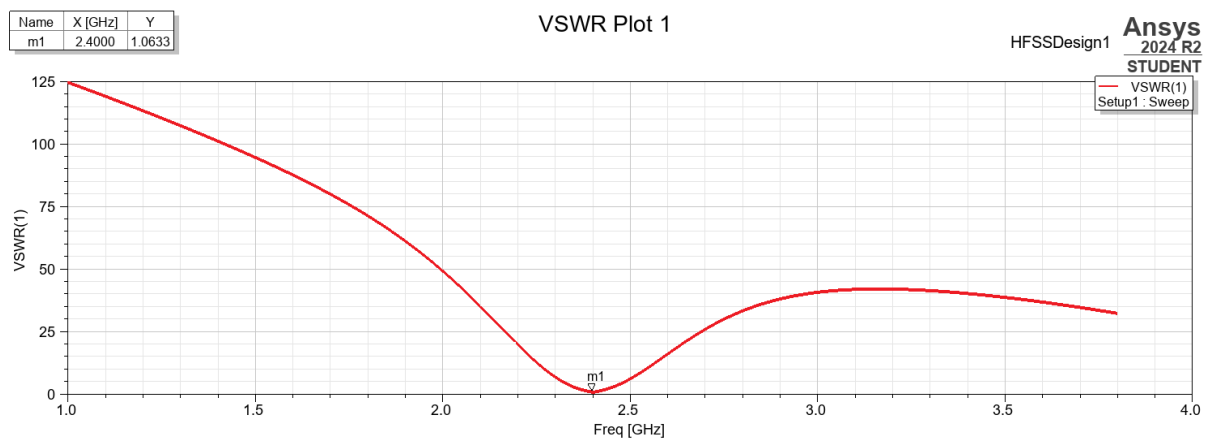
Upper frequency limit:

m3: 2.4311 GHz, where  $S_{11} \approx -9.9977$  dB

Calculated bandwidth =  $2.4311 - 2.3722 = 0.0589$  GHz  $\approx 58.9$  MHz

. The antenna can effectively operate across this range, covering multiple communication channels with acceptable return loss performance.

### III.4.2.2.VSWR:



*Figure III.7: Curve showing the variation of the Voltage Standing Wave Ratio (VSWR) as a function of frequency*

Notes on the curve:

The VSWR curve is used to evaluate the alignment of the antenna with the feed line, and is an indicator of the amount of power reflected from the antenna.

The ideal VSWR value is 1 (i.e., no reflected power). The closer the value is to 1, the more efficient the antenna is.

At around 2.4 GHz, a low VSWR value (close to 1) appears, indicating that the antenna is tuned to operate at this frequency.

There appears to be a bandwidth around this frequency where the value is less than 2

#### III.4.2.3. System le gain :

The figure presents the 3D system gain plot of the designed antenna simulated using ANSYS HFSS. This plot illustrates the spatial distribution of the total gain of the antenna at the specified operating frequency.

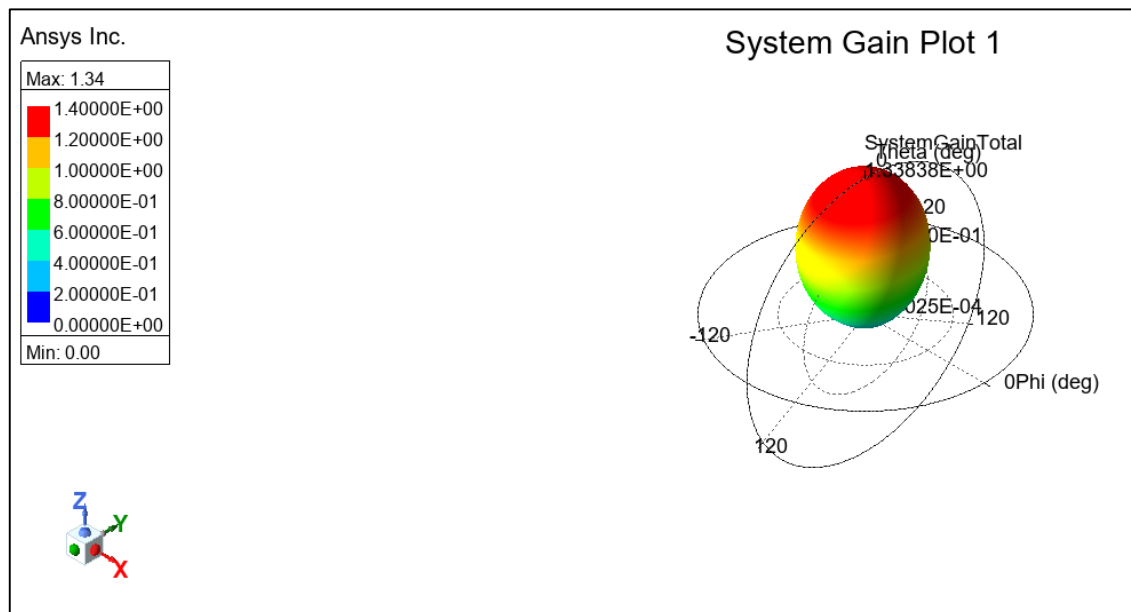


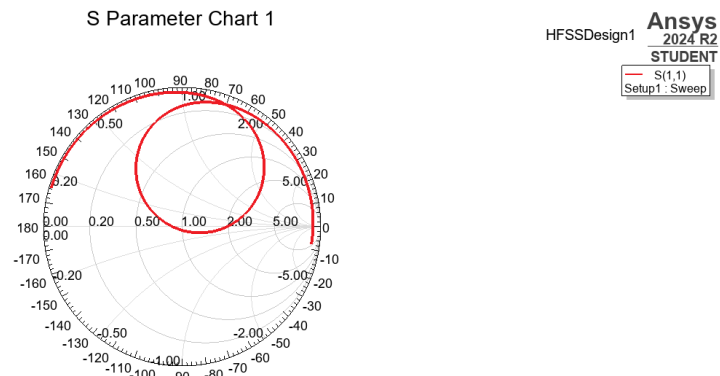
Figure III.8: 3D System Gain Plot .

It is evident from the plot that the antenna exhibits good directivity characteristics, with the radiation concentrated in a specific direction, which aligns with the expected behavior of microstrip patch antennas designed for the target frequency band. This is illustrated by the color gradient in the plot, where the red color indicates the maximum gain, and the other colors (green, blue) represent lower gain levels.

According to the simulation results, the maximum total gain achieved by the antenna is:

$$\text{Gain}_{\text{max}}=1.34 \text{ dB}$$

This value represents the peak gain in the main radiation direction. The plot also includes a 3D coordinate system (X, Y, Z) indicating the spatial directions, along with the angle axis



*Figure III.9: Smith Chart Analysis of the Reflection Coefficient ( $S_{11}$ ).*

representing horizontal angles. These references assist in analyzing the radiation pattern and understanding the antenna's performance more precisely. Such analysis is essential for evaluating the antenna's efficiency and ensuring its compliance with the requirements of the intended wireless application in terms of directionality, gain, and energy distribution in space.

The figure above represents a Smith chart of the dispersion coefficient of a designed patch antenna. This type of chart is widely used in the high-frequency field to analyze the harmonics of antennas with the feed line, and it gives a graphical representation of the relative impedance or reflection coefficient at different frequencies.

In this chart, we observe the following:

The red path shows the change in the reflection coefficient with frequency. Each point on this path represents a value at a specific frequency within the frequency range under study.

A path close to the center of the chart (point 0,0) indicates high harmonics at that frequency, meaning that most of the power is transmitted from the feed line to the antenna with minimal reflection.

When the path passes very close to the center, the reflection is low ( $|S_{11}|$  is close to zero), indicating that the antenna is well tuned at that frequency.

A path far from the center at other frequencies indicates poor harmonics and an increase in reflected power. Based on this diagram, the antenna's resonant frequency can be precisely determined—the frequency at which the point on the path is closest to the center of the circle. At this frequency, the antenna's input impedance is very close to the line impedance (usually 50 ohms), reflecting an efficient design.

## III.4.2.4. Gain Plot:

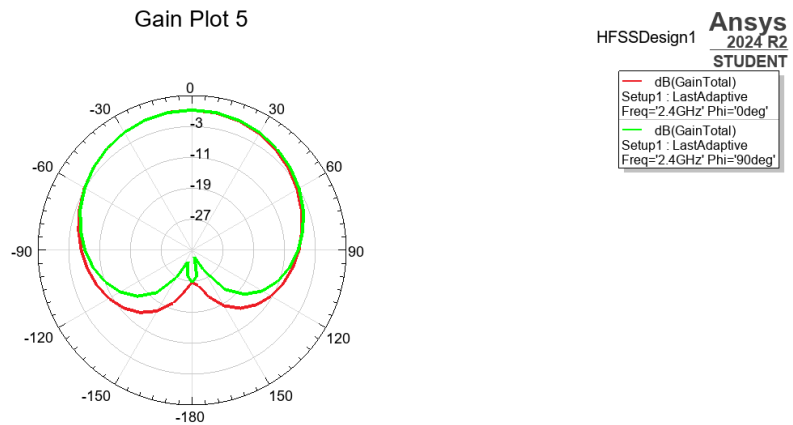


Figure III.10: Radiation Gain Plot of the Patch Antenna at 2.4 GHz in  $\phi = 0^\circ$  and  $\phi = 90^\circ$  Planes .

- **Radiation Gain Plot Analysis at 2.4 GHz:**

Figure (Gain Plot 5) illustrates the angular distribution of the total gain of the designed patch antenna at the frequency of 2.4 GHz. The gain is plotted for two different values of the azimuthal angle  $\phi$ :

Red curve: Represents the radiation pattern at  $\phi = 0^\circ$ . Green curve: Represents the radiation pattern at  $\phi = 90^\circ$ . From this plot, we can observe the following: The antenna exhibits a high gain in the vertical direction (at  $0^\circ$ ), indicating that the radiation is directed forward, which is expected from patch antennas with good directivity. The radiation pattern is relatively symmetric around the main axis, reflecting stable performance across different horizontal directions . The total gain in side and back directions is low, meaning that most of the radiated power is focused in the desired direction, enhancing the antenna's radiation efficiency. This type of radiation distribution is highly suitable for wireless communication applications such as Wi-Fi at 2.4 GHz, where directional radiation is beneficial for improved coverage and connectivity.

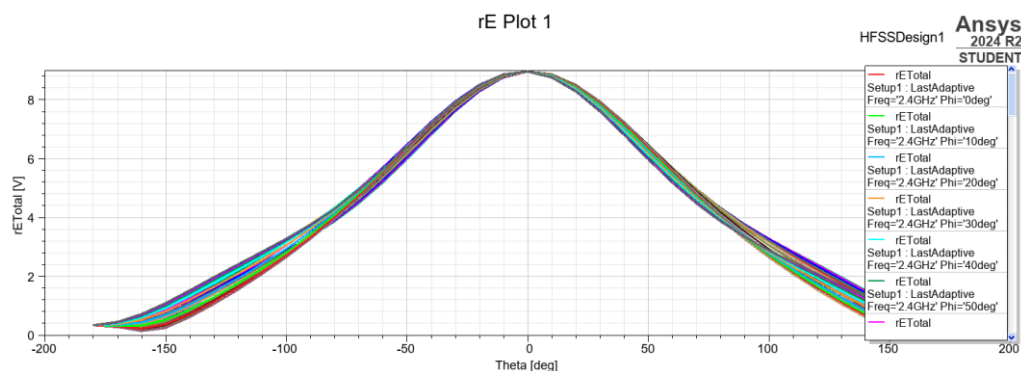
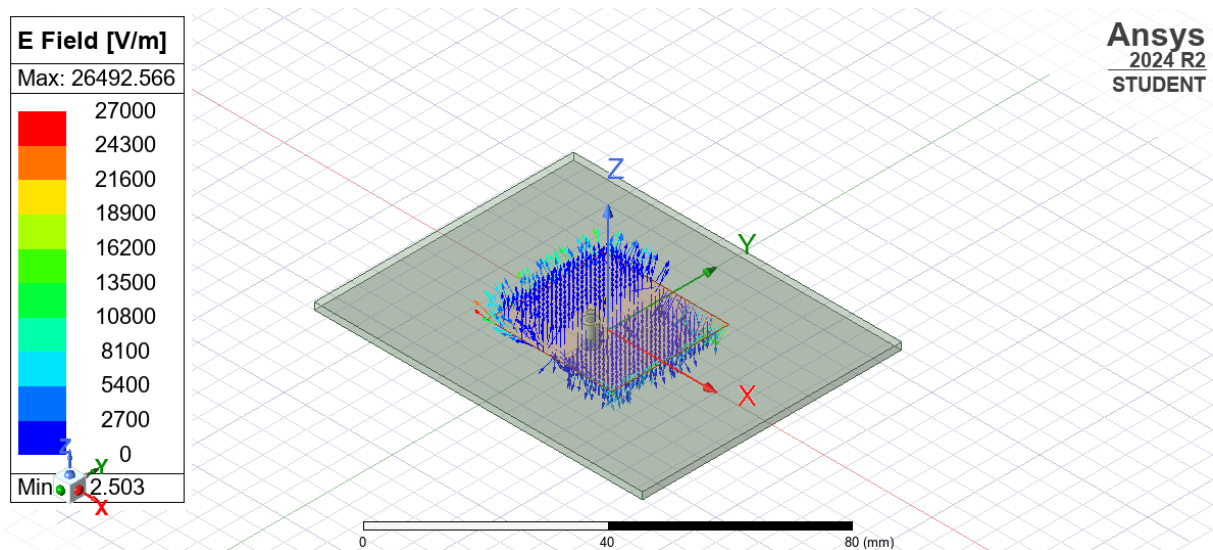


Figure III.11: Total Radiation Pattern ( $rE$  Total) of a 2.4 GHz Antenna .

- **Description:**

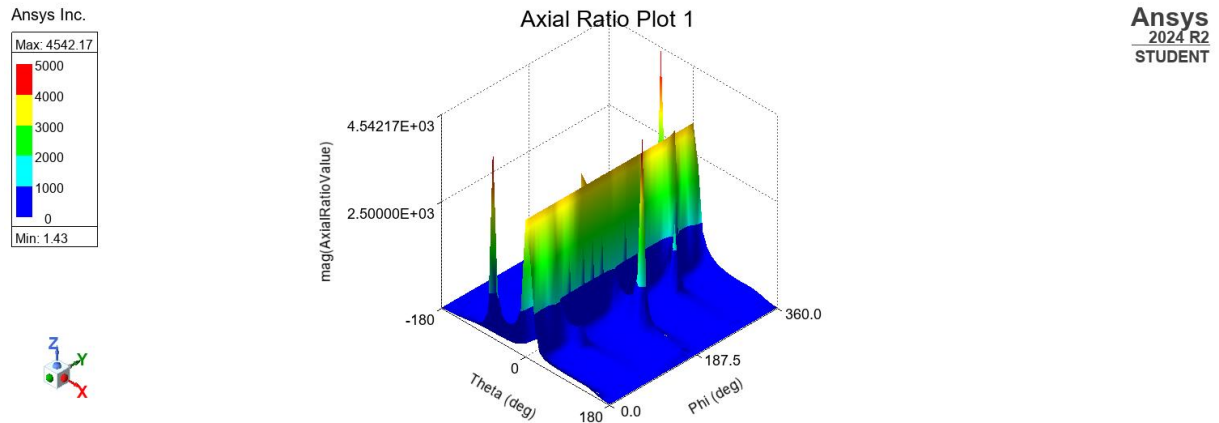
This figure illustrates the total radiation patterns of an antenna operating at 2.4 GHz for various Phi angles (ranging from  $0^\circ$  to  $50^\circ$ ). The results show that the maximum radiation occurs at  $\theta = 0^\circ$ , indicating that the antenna radiates most efficiently in the forward direction. Furthermore, variations in the Phi angle produce minimal changes in the radiation pattern, highlighting the antenna's consistent and stable radiation performance over the examined angular range. This behavior reflects the robustness of the antenna design and its suitability for wireless communication applications.

#### III.4.2.5. Electric Field Distribution



*Figure III.12: Electric Field Distribution.*

The electric field distribution on the surface of the patch antenna was obtained, as shown in the figure. It is observed that the electric field intensity varies across the surface of the antenna, with values ranging from 2.5 V/m as the minimum to 26492.6 V/m as the maximum. The color map illustrates the distribution of the field, where red areas indicate the highest field concentration, while blue areas indicate the lowest.



*Figure III.13: Axial Ratio Analysis of the Studied Antenna .*

This distribution clearly reflects the active resonant regions on the patch surface, which are typically concentrated around the edges or at the feeding points depending on the operating mode. It serves as an important indicator for understanding how electromagnetic waves are radiated from the antenna and helps evaluate the design's performance in terms of frequency matching and radiation efficiency.

The studied antenna was analyzed using a 3D plot that shows the distribution of the Axial Ratio, which is a key indicator for evaluating the quality of circular polarization. The ideal value for circular polarization is 1 (or 0 dB).

Plot Components: Theta (deg): Polar angle (from  $-180^{\circ}$  to  $180^{\circ}$ ).

Phi (deg): Azimuthal angle (from  $0^{\circ}$  to  $360^{\circ}$ ).

mag(AxialRatioValue): Absolute value of the axial ratio.

Color Scale: Blue color: Indicates good circular polarization. Warm colors (green to red): Indicate degradation in polarization quality.

Recorded Values: Maximum value (Max): 4542.17 Minimum value (Min): 1.43

The results show that the antenna achieves good circular polarization in certain directions (at the minimum value), while other areas exhibit clear degradation in polarization quality.

### **III.5.Conclusion**

In conclusion, this work, which addressed antenna analysis and design, can be said to have delved deeper into the technical characteristics that affect antenna efficiency and highlighted the essential role of careful design in improving overall performance, both in terms of signal gain, bandwidth, and suitability for the target frequencies.

Simulation results revealed that optimal antenna performance can only be achieved through a careful balance between geometric shape, material selection, and feeding techniques. Therefore, improving antenna design requires adopting innovative approaches that take into account the requirements of modern systems in terms of efficiency, size, and multiple frequencies

### **General Conclusion**

At the end of this work, we addressed one of the vital topics in the field of wireless communications, which is the design and simulation of printed antennas, with a focus on an antenna operating at a frequency of 2.4 GHz. Theoretical concepts related to antennas were reviewed, with particular emphasis on the characteristics and advantages of patch antennas, known for their ease of fabrication, small size, low cost, and light weight, making them suitable for a wide range of modern applications.

Analytical and simulation tools were employed to evaluate the electromagnetic performance of the antenna using the HFSS simulation software. A printed antenna was designed and its performance analyzed in terms of the reflection coefficient and the Voltage Standing Wave Ratio (VSWR). The results demonstrated that the designed antenna operates efficiently at the desired frequency, achieving acceptable values for these parameters, which confirms the success of the design and its compliance with theoretical expectations.

This work represents a significant step toward a deeper understanding of how to optimize the performance of printed antennas and paves the way for the development of more advanced designs that can meet the demands of future communication systems, especially in 5G and Internet of Things (IoT) applications

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