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CIRCULARLY POLARIZED CROSS-DIPOLE ANTENNA FOR S-BAND TELEMETRY

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(M. Sc. Thesis)

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ABSTRACT

In this thesis, a satellite telemetry antenna design that will operate in S-band (2060-2230 MHz) is presented. It is aimed for this antenna to have a return loss of $S11 \leq -10$ dB and axial ratio of $AR \leq 3$dB in the operating bandwidth. Also, half-power beamwidth of (65-75) º is desired. The geometry of the antenna is determined as cross-dipole to provide circular polarization since circular polarization is used in satellite telemetry. The antenna geometry consists of three main parts: the cross-dipole, feedline, and reflector. The cross-dipole arms were made with different lengths and asymmetrically bent to achieve circular polarization. A coaxial cable was used for feeding the antenna, with feeding accomplished via a microstrip transmission line. A defected ground plane structure was preferred over a simple uniform ground plane as a reflector. In the antenna design, parameters such as the angles of the dipole arms and the position of the reflector were carefully adjusted to optimize frequency performance and meet desired technical specifications. The proposed antenna was modeled and simulated using CST software, successfully achieving the targeted technical requirements. Also, a prototype has been manufactured and measured. The simulations and measurement results were compatible and it was confirmed that the proposed antenna was suitable for the desired telemetry station by providing the targeted technical requirements.

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S-BANT TELEMETRİ İÇİN DAİRESEL POLARİZASYONLU ÇAPRAZ DİPOL ANTEN

(Yüksek Lisans Tezi)

Aysu Başak ALTUĞ YILMAZ

GAZİ ÜNİVERSİTESİ
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ÖZET

Bu tezde, S-bandında (2060-2230 MHz) çalışacak bir uydu telemetri anteni tasarımı sunulmuştur. Bu antenin çalışma bant genişliğinde S11 ≤ -10 dB geri dönüş kaybına ve AR ≤ 3dB eksenel oranına sahip olması hedeflenmiştir. Ayrıca, (65-75) º'lik yarım güç hüzme genişliği istenmektedir. Uydu telemetrisinde dairesel polarizasyon kullanıldığından, antenin geometrisi dairesel polarizasyon sağlamak için çapraz dipol olarak belirlenmiştir. Anten geometrisi üç ana parçadan oluşmaktadır: çapraz dipol, besleme hattı ve reflektör. Çapraz dipol kolları farklı uzunluklarda yapılmış ve dairesel polarizasyon elde etmek için asimetrik olarak bükülmüştür. Anteni beslemek için bir koaksiyel kablo kullanılmış ve besleme bir mikroşerit iletim hattı üzerinden sağlanmıştır. Basit düzgün bir toprak düzlemi yerine deforme edilmiş yapılı toprak düzlemi reflektör olarak tercih edilmiştir. Anten tasarımında, dipol kollarının açıları ve reflektörün konumu gibi parametreler frekans performansını optimize etmek ve istenen teknik özellikleri karşılamak için dikkatlice ayarlanmıştır. Önerilen anten, hedeflenen teknik gereksinimlere başarıyla ulaşarak CST yazılımı kullanılarak modellenmiş ve simülsyonu yapılmıştır. Ayrıca, hedeflenen antenin prototipi yapılmış ve ölçümler alınmıştır. Simülasyonlar ve ölçüm sonuçlarının uyumlu olduğu ve önerilen antenin hedeflenen teknik gereksinimleri sağladığı gözlemlenmiştir.

Bilim Kodu : 93415
Anahtar Kelimeler : Çapraz dipol, anten, bant genişliği, polarizasyon, ışıma örüntüsü, empedans uyumlandırması, S-parametreleri, eksenel oran
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SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below, along with their explanations.

Symbols	**Explanations**
c	Speed of light
dB	Decibel
EHz	Ekzahertz
f	Frequency
GHz	Gigahertz
Hz	Hertz
kHz	Kilohertz
km	kilometer
L	Length
m	meter
MHz	Megahertz
mm	millimeter
P	Power
R	Radius
s	Second
U	Radiation Intensity (W/unit solid angle)
V	Volt
V/m	Volt/meter
W	Watt
Ω	Ohm
λ	Wavelength
°	Degree/Deg.

Abbreviations	**Explanations**
2D	Two Dimensions

Abbreviations	**Explanations**
3D	Three Dimesions
AM	Amplitude Modulation
AR	Axial Ratio.
CAN	Controller Area Network
CP	Circular Polarized/Polarization.
DP	Dual-Polarized/Polarization.
EHF	Extremely High Frequency
EM	Electromagnetic
EMC	Electromagnetic Compatibility
FM	Frequency Modulation
FNBW	First-Null Beamwidth
GNSS	Global Navigation Satellite Systems
GPRS	General Packet Radio Service
GEO	Geosynchronous Equatorial Orbit
GPS	Global Positioning Systems.
HF	High Frequency
HPBW	Half Power Beamwidth
IEEE	Institute of Electrical and Electronics Engineers
LF	Low Frequency
LHCP	Left-Hand Circular Polarization
MF	Medium Frequency
NA	Network Analyzer
PCB	Printed Circuit Board
PTFE	Poli Tetra Flor Etilen
RF	Radio Frequency
RFID	Radio Frequency Identification
RHCP	Right-Hand Circular Polarization
SHF	Super High Frequency
SWR	Standing Wave Ratio
UHF	Ultra High Frequency
VHF	Very High Frequency
VLF	Very Low Frequency

Abbreviations	**Explanations**
VNA	Vector Network Analyzer
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
TV	Television

1. INTRODUCTION

Communication is a fundamental human need that has evolved from ancient times to today. Over time, developments have occurred to meet this need and provide convenience. In humanity's early years, people communicated over long distances by shouting or using smoke signals. With the discovery of electricity in subsequent years, communication over long distances began. Initially carried out via electrical wires, this wired communication method has gradually given way to the wireless communication systems we use today, aided by technological advancements [1]. Communication systems consist of three basic elements: transmitters that send the desired information. This physical transmission channel carries the information, and receivers capture and interpret the transmitted information to make it meaningful. Communication systems are classified into two categories based on the transmission medium used: wired and wireless. In wired communication, conductive cables are used as the transmission medium, whereas in wireless communication, the transmission medium is the atmosphere. In wireless communication, data received from the transmitter is conveyed to the antenna, converted into electromagnetic waves, and propagated through the atmosphere. The electromagnetic waves captured by the receiving antenna in the transmission medium are interpreted into meaningful information by the receiver [2].

Alongside wireless communication, antenna systems have emerged as the most critical components of this system. An antenna is defined as “a usually metallic device as a rod or wire, for radiating or receiving electromagnetic waves.” The Institute of Electrical and Electronics Engineer (IEEE) Standard Definitions of Terms for Antennas (IEEE Std 145–1983) defines the antenna as “a means for radiating or receiving radio waves.” [3]. Today, antennas are used in lots of different wireless communication systems. Examples of these systems are broadcasting services, satellite communications, telemetry operations, wireless local area networks (WLANs), mobile communications, Global Navigation Satellite Systems (GNSS), Radio Frequency identification (RFID), etc.

A good design of the antenna can enhance overall system performance. To achieve optimal antenna performance, system requirements must be carefully defined. Primarily, an antenna should be designed according to its intended use. The most critical parameter in antenna design is identifying on which platform and within which frequency ranges the antenna will operate. For instance, an antenna intended for satellite tracking must have a radiation pattern capable of receiving broadcasts within the frequency ranges transmitted by that satellite. Subsequently, decisions should be made on the most suitable antenna type that can operate within these frequency ranges and its dimensions should be determined accordingly.

In general terms, frequency is defined as the number of occurrences of a repeating event per unit of time. In the context of electromagnetic waves or signals, frequency specifically refers to the rate at which oscillations (cycles) occur in the waveform. It is measured in hertz (Hz), where one hertz equals one cycle per second. Higher frequencies correspond to shorter wavelengths in the electromagnetic spectrum. In the electromagnetic spectrum, frequency determines the type of wave and its properties. Radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays are electromagnetic waves. These types are categorized based on their frequencies, which range from very low frequencies (like 3 kHz for some radio waves) to extremely high frequencies (like 300 EHz for gamma rays).

An electromagnetic wave's wavelength (λ) is calculated using the formula Eq. 1.1.

$$\lambda = c/f \tag{1.1}$$

In Eq. (1.1) λ is the wavelength, c is the speed of light which is approximately 3×10^8 m⁄s and f means the frequency. The frequency has a wide spectrum between 3kHz and 300 GHz. The frequencies in this range are divided according to certain parameters. The frequency range between 1-40 GHz is called satellite frequency. This region is also divided into bands. The S-band is the most widely used band in satellite communications, which covers the range of 2-4 GHz. This thesis will draw attention to the range between 2060-2230 MHz.

Telemetry systems are used for remote wireless monitoring or control of a system [4]. Today, this infrastructure is utilized in various aircraft, ground vehicles, and missile systems.
Today, parallel to the development of communication systems, antennas have also been improved, and antennas with different features have been produced for various applications. One of these antenna types is the cross-dipole antenna. The history of this antenna began in the 1930s. George Brown created the first cross-dipole antenna, which he called the "turnstile antenna". A new type of cross-dipole antenna was developed in 1961 for circular polarization radiation by using a single feed. Cross-dipoles with the necessary 90° phase

difference between them started to be fed by two separate ports in the 2000s to produce dual polarization radiation [5].

In this thesis, the aim is to design a circularly polarized cross-dipole antenna operating in the S-Band. The designed antenna is intended to operate in a telemetry ground station. The designed antenna consists of a cross-dipole with asymmetric lengths, a reflector, and a transmission line. These three components are located on the same coaxial cable. The angle and distance between the reflectors and the dipoles affect the antenna's radiation pattern, axial ratio, and reflection coefficient. This thesis aims to determine the most optimized antenna geometry through simulations at different distances and angles.

The antenna design we aim for here is to have an axial ratio value of 3dB and below in the specified S-band range (2060-2230 MHz). In addition, the Half-Power-BeamWidth (HPBW), that is, the value at the point where the power drops by 3 dB in the radiation diagrams of the antenna in this range, should be between (65º-75º). All antenna analyses will be made in this S-Band range and since the actual operating frequency range is 2060-2230 MHz, we aim to reach the best values at those points which is the center frequency of this range. Then, we will design the antenna with the geometry we reached in the simulation in real life and compare the simulation results with the measurement results with the help of Network Analyzer (NA).

In this study, general information about the thesis is provided in Section 1. In Section 2, brief information about the parameters that need to be determined for antenna design is given. In Section 3, antenna and cross-dipole antenna history and advantages are described. In Section 4, the geometry of the designed antenna based on the selected parameters is described. In Section 5, the simulation results and measurement results of the designed antenna are shared. CST software was used as the simulation environment. In Section 6 the last section, the obtained simulation and measurement results are evaluated and the outcomes are discussed.

2. THE GENERAL ANTENNA PARAMETERS

In this section, some terms related to antenna parameters will be discussed to provide preliminary information for the other sections. Each antenna is designed to be used under specific conditions for a particular purpose. The suitability of an antenna for a specific purpose is determined by its electrical characteristics, and thus by the antenna parameters that define its behavior within the system. Although many parameters describe the electrical properties of antennas, this section will examine the main parameters required for this study and sufficiently evaluate the suitability of the designed antenna for our purpose.

2.1. Definition and Working Principle of Antenna

Webster's Dictionary defines an antenna as a metallic device, such as a rod or wire, used for radiating or receiving radio waves. The IEEE Standard Definitions of Terms for Antennas (IEEE Std 145–1983) defines the antenna or aerial as a method for radiating or receiving radio waves. Essentially, the antenna serves as the connection between free-space and a guiding device, as shown in Figure 2.1. The guiding device, whether a coaxial line or a hollow pipe (waveguide), is responsible for transmitting electromagnetic energy from the source to the antenna or from the antenna to the receiver. This results in transmitting antenna in the former case and a receiving antenna in the latter [6].

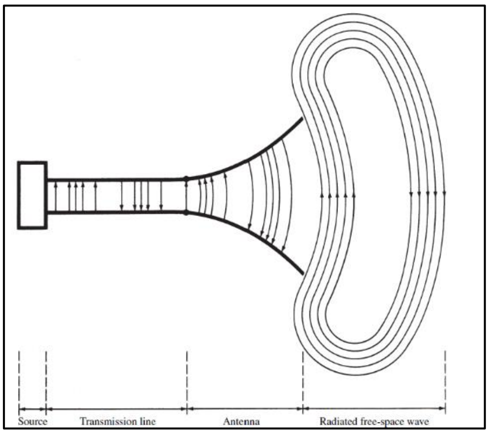


Figure 2.1. Antenna [6]

An antenna device can efficiently and desiredly radiate and receive electromagnetic radiation. It is a key component of a radio system. Although metal is the typical material, it can also be built of other materials. For instance, dielectric resonator antennas have been created using ceramic materials [7].

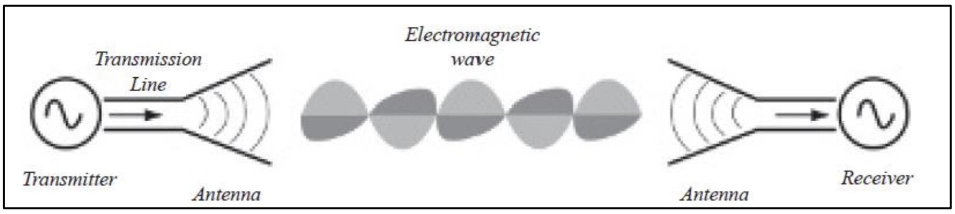


Figure 2.2. A radio system [7]

Figure 2.2. shows a typical radio communication system. A transmission line with a typical characteristic impedance of 50 Ω is used to carry the modulated and amplified source data to the transmit antenna. In an effective and desired manner, the antenna radiates the information as an electromagnetic wave to the destination, where it is picked up by the receiver and transmitted to the receiver via a different transmission line. After the signal has been demodulated, the receiver recovers the original message [18]. Antenna and feed line integration is useful in certain applications (e.g., aircraft, hand portables) when space is very limited. Other applications, like receiving TV broadcasts, require the use of a long transmission line because the antenna is far from the receiver.

To understand antenna theory thoroughly requires a considerable amount of mathematics. The configuration for Figure 2.1. is depicted in Figure 2.3. as a transmission-line Thevenin equivalent.

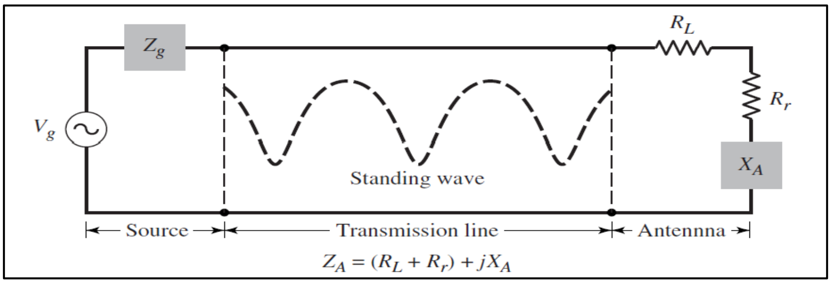


Figure 2.3. Thevenin equivalent of the transmission line of an antenna [6]

It consists of an ideal generator representing the source, a transmission line with characteristic impedance Z_C,and an antenna load Z_A connected to the transmission line. The antenna load is defined by using the formula Eq. 2.1.

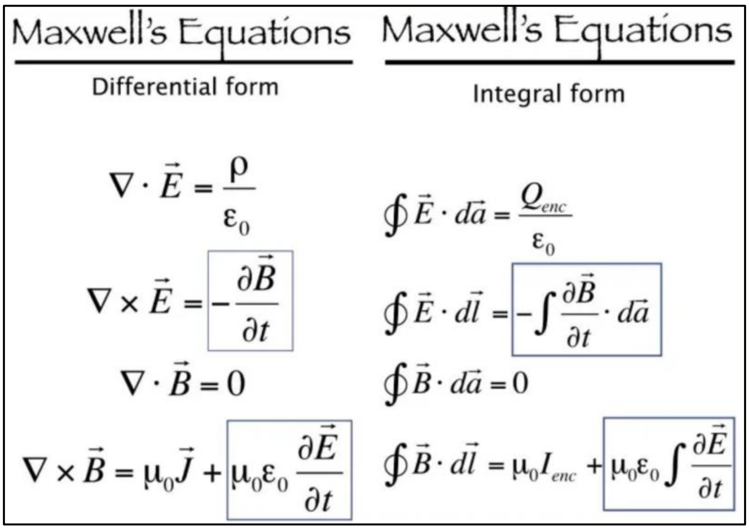
$$\mathrm{Z_A} = [(\mathrm{R_L} + \mathrm{R_r}) + \mathrm{jX_A}] \qquad (2.1)$$

The load resistance R_L represents the conduction and dielectric losses related to the antenna structure. R_r is known as radiation resistance, X_A is the antenna reactance and it represents the antenna's radiation. However, in a practical applications system, there are losses from reflections (mismatch) at the line-antenna interface and conduction-dielectric losses because of the lossy nature of the transmission line and the antenna.

Standing waves are constructive and destructive interference patterns that are produced inside the transmission line by the reflected waves from the interface and the traveling waves from the source toward the antenna. These patterns represent pockets of energy storage and concentrations that are characteristic of resonant devices. The transmission line may function primarily as an energy storage component rather than a wave-guiding and energy-transporting device if the antenna system is not well-constructed. Arching within the transmission lines may result from standing waves with sufficiently high maximum field intensities.

2.2. The History of Antenna

Work on antennas began many years ago. History began with James Clerk Maxwell who unified the theories of electricity and magnetism and eloquently represented their relations through a set of profound equations as known as Maxwell’s Equations [6]. In 1873, Maxwell published his first work. He demonstrated that light was electromagnetic and that light and electromagnetic waves travel by wave disturbances of the same speed.



Maxwell's Equations

Differential form

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \boxed{\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}}$$

Maxwell's Equations

Integral form

$$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$$

$$\oint \vec{E} \cdot d\vec{l} = \boxed{-\int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{a}}$$

$$\oint \vec{B} \cdot d\vec{a} = 0$$

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \boxed{\mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}}$$

Figure 2.4. The Maxwell's equations [17]

The first wireless electromagnetic system was demonstrated by the German physicist Professor Heinrich Rudolph Hertz in 1886. He conducted a well-known antenna experiment in 1887. In this experiment, he was able to create a spark in the gap of a transmitting λ/2 dipoles at a wavelength of 4 m. This spark was then detected in the gap of a nearby loop. The original intention of his experiment was to demonstrate the existence of electromagnetic radiation [7]. The experiment setup is shown in Figure 2.5. A dipole with two conducting balls at the ends was connected to a variable voltage source inside the transmitter. For both spark production and circuit resonance, the distance between the balls might be changed. The voltage created a spark or break-down discharge when it reached a particular point.

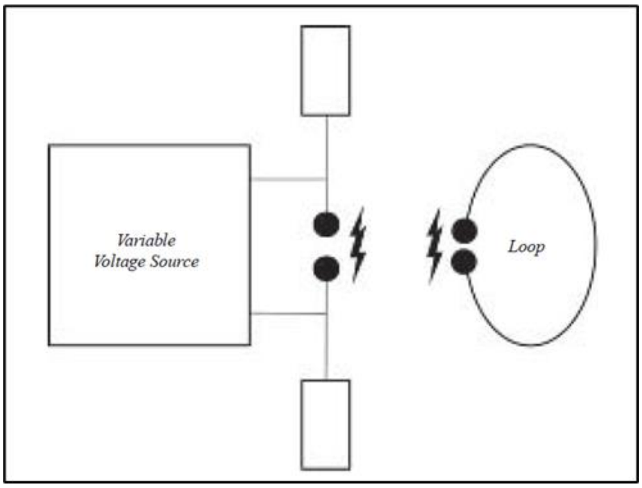


Figure 2.5. The experiment setup [6]

The receiver is a simple ring consisting of two identical conducting circles. The gap between the balls was carefully adjusted to ensure a good spark. He placed the device in a dark box so that the spark could be seen clearly. In his experiment, when a spark occurs in the transmitter, he sees a spark in the path of the receiver at the same time. It was proven that information from location A (transmitter) is transmitted wirelessly with electromagnetic waves to location B (receiver). The frequency unit is named Hertz after him.

When Heinrich Hertz did his experiments in the laboratory, he was not sure what radio waves could be used. The Italian inventor, Guglielmo Marconi, developed and commercialized wireless technology and introduced a radio telephone system, which became the basis for the establishment of several telephone companies around the world.

Even though World War II resulted in a new era for antennas, developments in computer architecture and technology from the 1960s to the 1990s significantly influenced the development of contemporary antenna technology, and they are predicted to continue to have an even bigger impact on antenna engineering well into the twenty-first century. Numerical techniques were developed starting mostly in the early 1960s, enabling highly precise analysis and design of complex antenna system configurations that were previously unachievable.

2.3. Antenna Types

There are many different types of antennas used today. These include dipole antennas, helix antennas, patch antennas, and more.

2.3.1. Helix antenna

A helical antenna, or helix antenna, consists of a conducting wire wound into the shape of a helix. It can be used in two modes: normal mode and axial mode. In the normal mode, the antenna radiates perpendicular to the axis of the helix and is typically used for Very High Frequency (VHF) and Ultra High Frequency (UHF) applications. In the axial mode, the antenna radiates along the axis of the helix, providing circular polarization and a high gain, making it ideal for satellite and space communication.

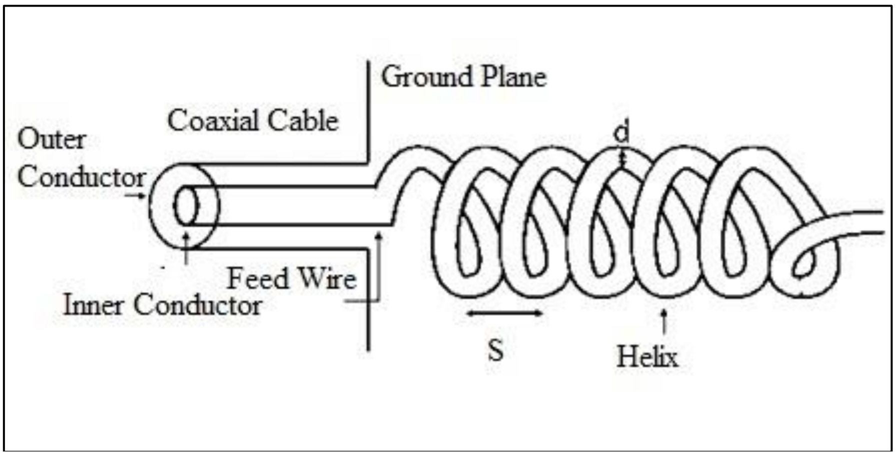


Figure 2.6. Helix antenna [9]

2.3.2. Dipole antenna

A dipole antenna is one of the simplest and most commonly used types of antennas. It consists of two conductive elements such as metal wires or rods that are typically equal in length and oriented in a straight line. The most basic form is the half-wave dipole, where each element is a quarter wavelength long. Dipole antennas are omnidirectional, radiating signals uniformly in all directions perpendicular to the antenna. They are widely used in applications such as radio and television broadcasting, wireless communications, and as a reference antenna in antenna theory [3].

2.3.3. Patch antenna

A patch antenna is a flat rectangular sheet of metal mounted over a larger sheet of metal called a ground plane. It is also called a microstrip antenna, the patch and ground plane are separated by a dielectric material. The general structure of the patch antenna is shown in Figure 2.7. The dimensions of the patch (w, t, and l) affect the polarization and frequency range of the antenna. Patch antennas are commonly used in compact and lightweight designs, such as in mobile phones, Global Positioning System (GPS) devices, and Wireless Fidelity (Wi-Fi) routers. They are known for their ease of fabrication, low profile, and ability to be integrated into printed circuit boards [10].

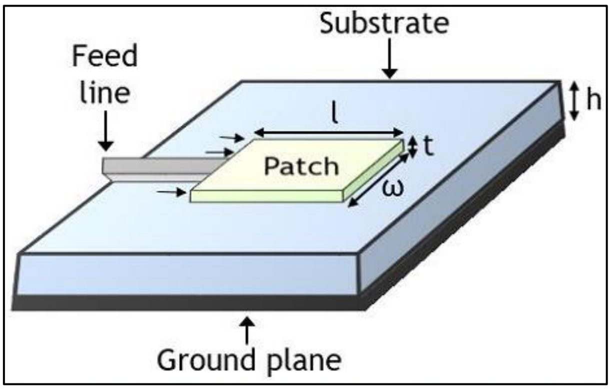


Figure 2.7. Patch antenna [11]

2.3.4. Cross-Dipole antenna

A cross-dipole antenna is a configuration of two dipole antennas placed orthogonally (cross) with each other. This arrangement allows for circular or elliptical polarization, depending on the phasing of the signals fed to the two dipoles. Cross-dipole antennas are often used in satellite and space communications where polarization diversity is essential to combat the effects of signal fading and to ensure reliable signal transmission and reception. Cross-dipole antennas can work in all radiation patterns when properly designed. These radiation patterns are defined as isotropic, omnidirectional, dual-polarized (DP), and circular polarized (CP) radiation [5]. Different structures of cross-dipole antenna are shown in Figure 2.8. and in Figure 2.9.

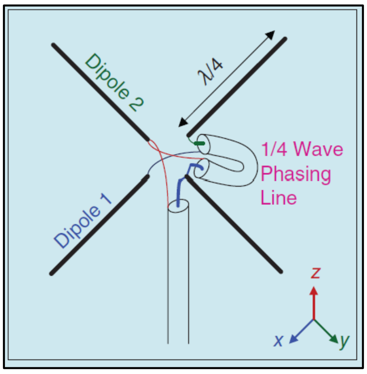


Figure 2.8. Cross-Dipole 1

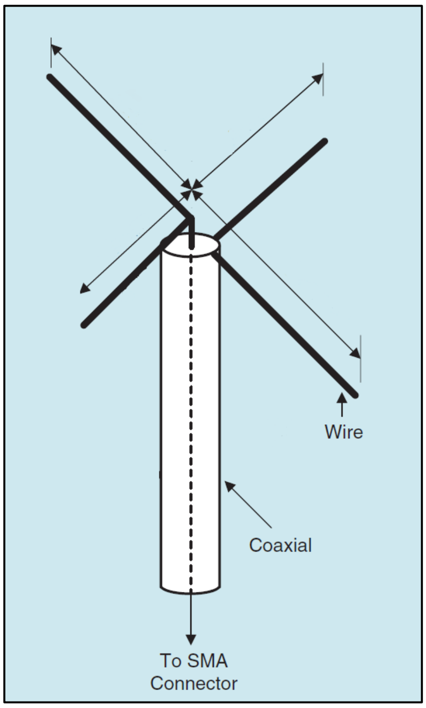


Figure 2.9. Cross-dipole 2 [5]

2.4. Frequency Range

Frequency ranges in antenna design are fundamental parameters that determine antenna performance. Each communication application or system is defined by specific frequency ranges, directly influencing the antenna's operational principles and geometry. For instance, common frequency ranges used in wireless communication systems typically encompass Radio Frequency (RF) and microwave bands. RF bands generally cover frequencies ranging from approximately 3 kilohertz (kHz) to 300 Gigahertz (GHz), serving a wide range of applications such as Amplitude Modulation (AM) radio, Frequency Modulation (FM) radio, and television broadcasts. Microwave bands, on the other hand, typically operate in the GHz range and are used in applications requiring high data transfer rates, such as radar systems, wireless communication systems, and remote sensing. RF bands are described in Table 2.1. and in Figure 2.10.

Table 2.1. Radio frequency spectrum [12]

Designation	Abbreviation	Frequencies	Wavelengths
Very Low Frequency	VLF	3 kHz – 30 kHz	100 km – 10 km
Low Frequency	LF	30 kHz – 300 kHz	10 km – 1 km
Medium Frequency	MF	300 kHz – 3MHz	1 km – 100 m
High Frequency	HF	3 MHz – 30 MHz	100 m – 10 m
Very High Frequency	VHF	30 MHz – 300 MHz	10 m – 1 m
Ultra High Frequency	UHF	300 MHz – 3 GHz	1 m – 100 mm
Super High Frequency	SHF	3 GHz – 30 GHz	100 mm – 10 mm
Extremely High Frequency	EHF	30 GHz – 300 GHz	10 mm – 1mm

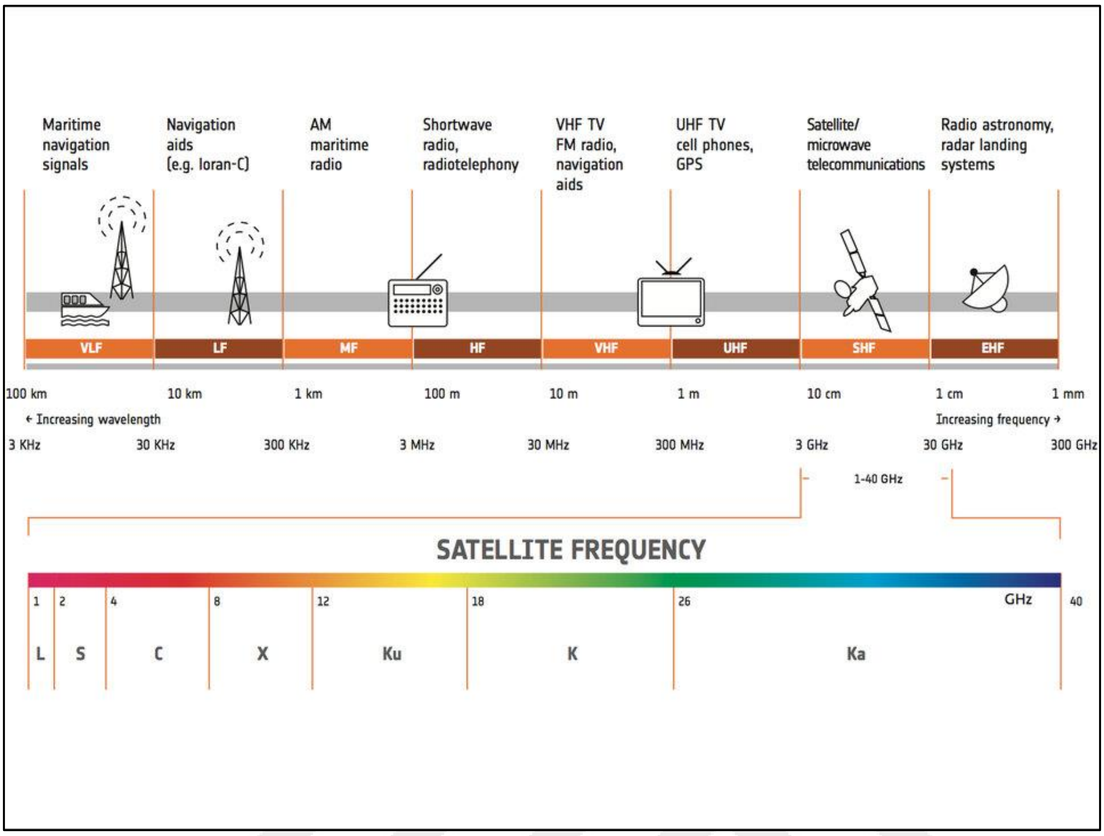


Figure 2.10. Radio frequency spectrum [12]

As shown in Figure 2.10, there is an additional frequency range between 1 to 40 GHz. It is called “Satellite Frequency”. These frequency ranges and bands are essential in different aspects of wireless communication, offering a variety of propagation characteristics, data transmission capacities, and application suitability. Understanding these ranges helps in designing and deploying effective communication systems.

- L Band (1 GHz to 2 GHz): Used in GPS, satellite communications, and some mobile phone networks.
- S-Band (2 GHz to 4 GHz): Utilized in weather radar, satellite communications, and some Wi-Fi bands.
- C Band (4 GHz to 8 GHz): Commonly used for satellite communications and some radar applications.
- X Band (8 GHz to 12 GHz): Used in radar and satellite communications, especially for military purposes.
- Ku Band (12 GHz to 18 GHz): Widely used for satellite television broadcasting and VSAT (Very Small Aperture Terminal) systems.

- Ka-Band (26.5 GHz to 40 GHz): Employed in high-frequency satellite communications and some radar systems.

Furthermore, for specialized applications like satellite communication, antennas designed for specific frequency ranges must be optimized to effectively detect satellite broadcasts and transmit data. Therefore, determining the correct frequency ranges for each communication system and designing antennas accordingly is crucial for maximizing system efficiency and performance.

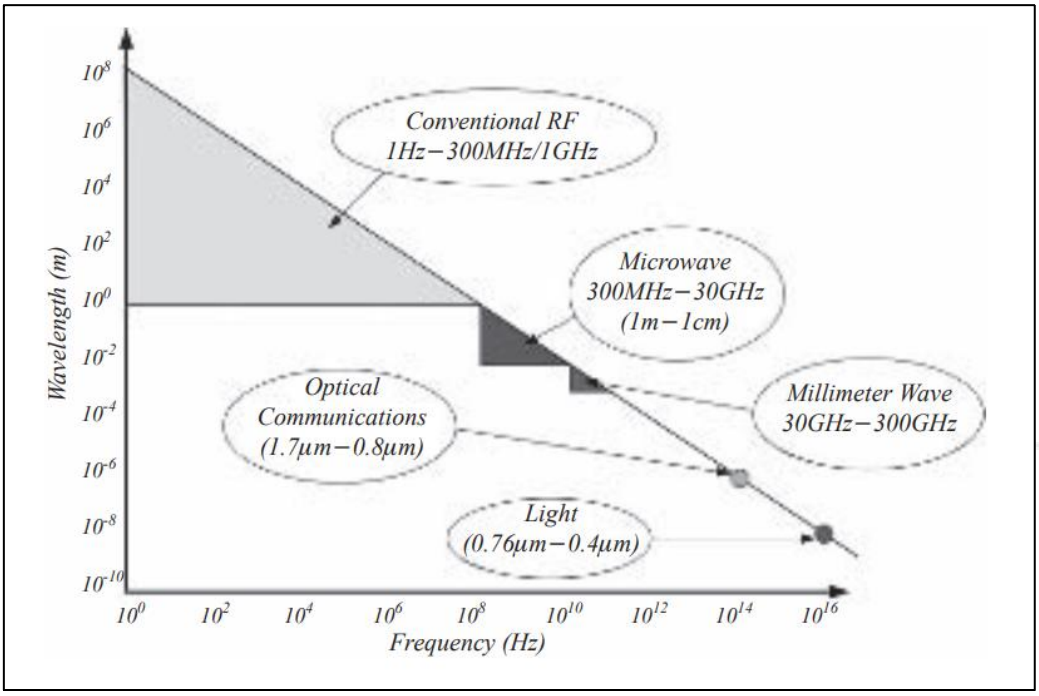


Figure 2.11. Wavelength vs. frequency graphic

In Figure 2.11, how the frequency is linked to the wavelength is shown. In this figure frequency and wavelength are both plotted on a logarithmic scale. The advantage of doing this is that we can see clearly how the function is changed, even over a very large scale. [7]

Since the signals we work with change greatly in magnitude, logarithmic scales are frequently utilized in radio frequency engineering and the antenna community. Typically, signal power is stated in decibels (dB) and is described as shown in Eq. 2.2.

$$\mathrm{P(dBW)}=10\log_{10}\frac{\mathrm{P(W)}}{\mathrm{1W}} \text{ or } \mathrm{P(dBm)}=10\log_{10}\frac{\mathrm{P(W)}}{\mathrm{1mW}} \qquad (2.2)$$

2.5. Polarization

Polarization refers to the orientation of the electric field vector of an electromagnetic wave. It's a key characteristic in antenna design and signal transmission, influencing the propagation of waves and the interaction with receiving antennas. Proper polarization alignment between transmitting and receiving antennas is critical for efficient communication.

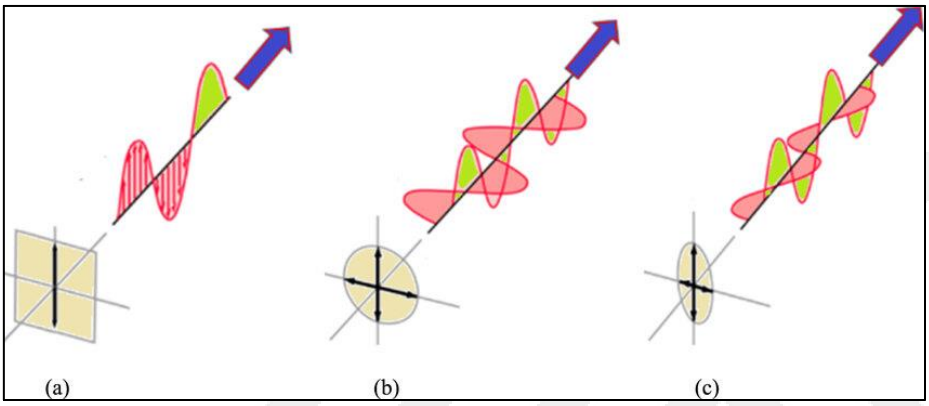


Figure 2.12. a) Linear polarization   b) Circular polarization c) Elliptical polarization

2.5.1. Linear polarization

The electric field vector remains in a single plane as the wave propagates. The plane may be oriented at any fixed angle, vertical, or horizontal. The electric field is parallel to the Earth's surface in horizontal polarization. It is frequently utilized in television antennas for terrestrial broadcasts. The electric field in vertical polarization is perpendicular to the surface of the Earth. FM radio and mobile communications both frequently use it.

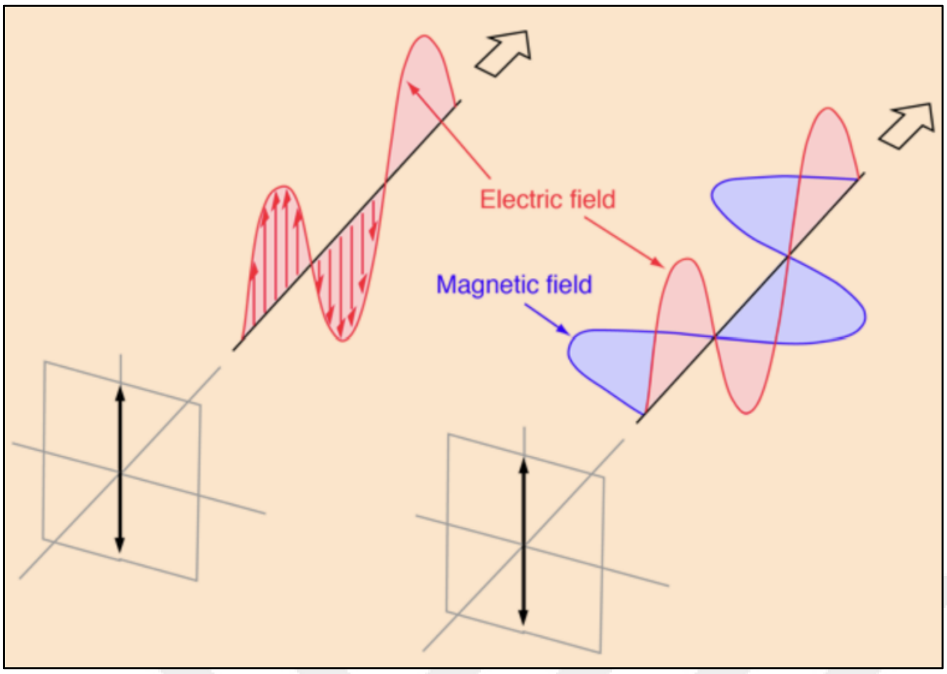


Figure 2.13. Linear polarization [13]

2.5.2. Circular polarization

The electric field vector rotates circularly as the wave propagates, creating a helical pattern. The direction of propagation is shown in Figure 2.14. The rotation can be clockwise, called Right-Hand Circular Polarization (RHCP), or counterclockwise called Left-Hand Circular Polarization (LHCP). It is effective in environments where signal reflections and orientations can vary, such as in satellite and mobile communications. Circular polarized (CP) antennas are a common approach to alleviate orientation dependence in far-field applications. For example, satellite and terrestrial communication systems employ CP antennas to maximize the polarization effectiveness component of the link budget. [14].

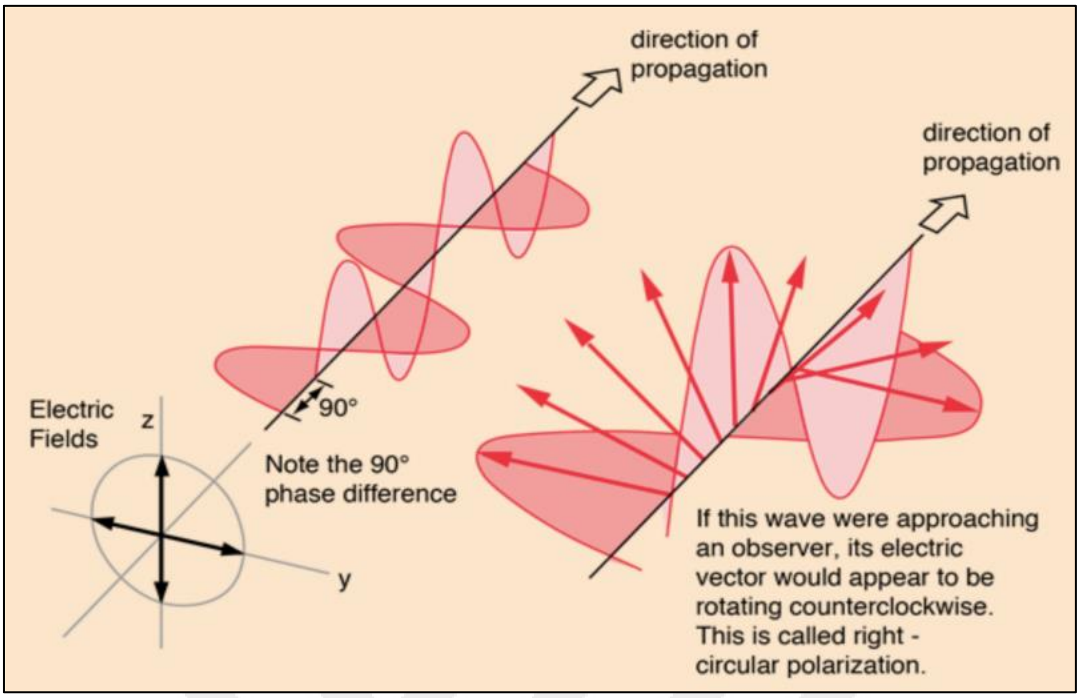


Figure 2.14. Circular polarization [13]

2.5.3. Elliptical polarization

A generalized form of polarization where the electric field describes an ellipse in any given plane perpendicular to the direction of propagation. It can be seen as a combination of linear and circular polarization. It is used in specialized communication systems where specific polarization characteristics are needed to optimize signal strength and reduce interference. Elliptical polarization offers flexibility in signal propagation characteristics, allowing for more robust communication in diverse environments.

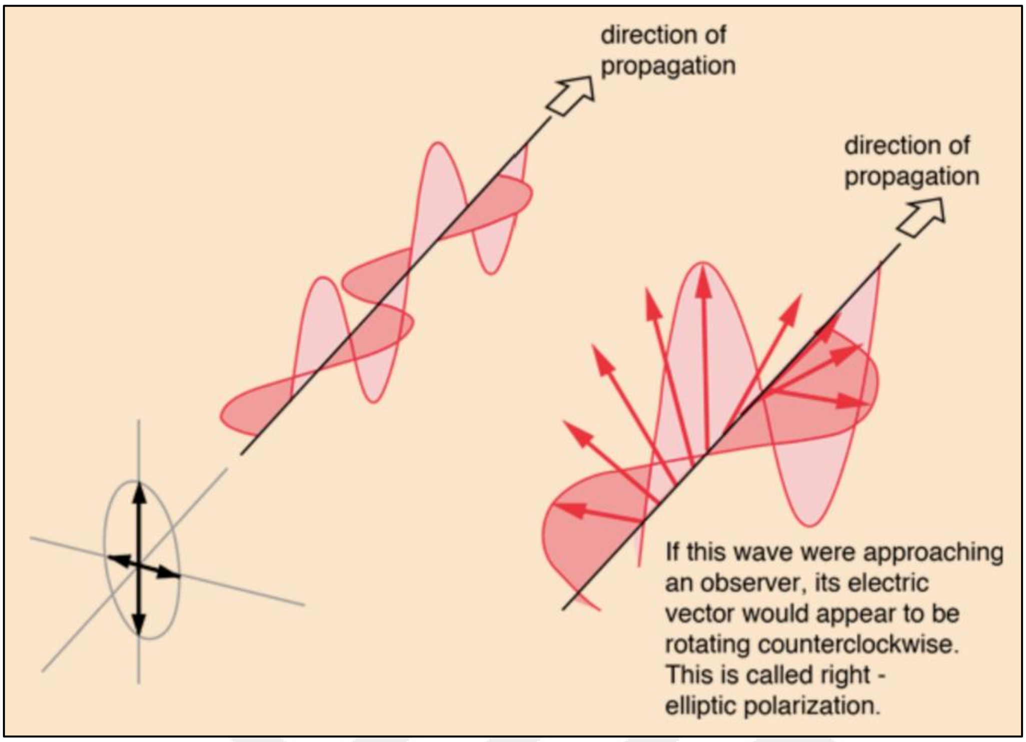


Figure 2.15. Elliptical polarization [13]

2.6. Radiation pattern

The radiation pattern is a visual representation of the signal generated by an antenna. The distribution of radiated power in space is shown. It is a critical characteristic that describes how an antenna radiates or receives energy. It helps in understanding the performance of the antenna in different directions. Understanding the radiation pattern of an antenna is crucial for designing and optimizing communication systems. It provides insights into how an antenna distributes energy in space, helping engineers ensure efficient and effective signal transmission and reception. The coordinate system that presents the radiation pattern is shown in Figure 2.16. The 3D pattern is an excellent illustration of the radiated field distribution as a function of angle θ and φ in space [7].

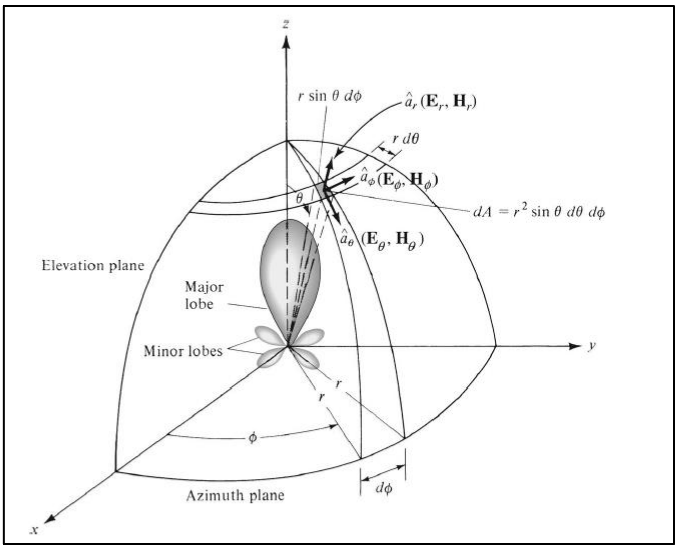


Figure 2.16. The coordinate system for analysis of the antennas [6]

There are 3 types of radiation patterns. These are isotropic, directional, and omnidirectional.

An isotropic radiation pattern is an idealized pattern that radiates power uniformly in all directions. It serves as a reference point for measuring real antennas. It is used as a theoretical model to compare the performance of actual antennas.

Directional radiation pattern shows greater radiation in specific directions. This pattern is common in practical antennas designed to focus energy in certain areas. It is used in applications where targeted coverage is needed, such as satellite dishes, parabolic antennas, and Yagi-Uda antennas.

Omnidirectional radiation pattern radiates power uniformly in one plane (typically horizontal) but varies in another plane (typically vertical). It is used in applications like mobile base stations, Wi-Fi routers, and whip antennas where 360 º horizontal coverage is desired.

2.6.1. Field region

The free space around the antenna is divided into 3 regions;

a) Reactive near-field region
b) Radiating near-field (Fresnel) region
c) Far-field (Fraunhofer) region

The borders separating these regions are not unique. However, various criteria have been determined to define the regions and these criteria are widely used. The boundaries are shown in Figure 2.17. The λ is the wavelength and L is the largest dimension of the antenna.

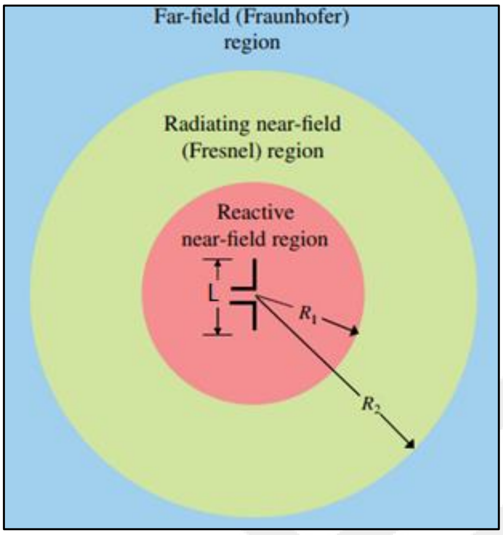


Figure 2.17. Antenna field regions

The reactive near field region is defined as "that part of the near field region immediately surrounding the antenna where the reactive field is dominant". It is the nearest region of the antenna and is defined as R_1 with this given formula in Eq. 2.3.

$$R_1=0.62\sqrt{L^3/\lambda} \tag{2.3}$$

Radiating near-field (Fresnel) region is defined as “that region of the field of an antenna between the reactive near-field region and the far-field region. It defines between R_1 and R_2. The R_2 defines as $2\mathrm{L}^2/\lambda$.

The region known as the far field (Fraunhofer) is where the angular field distribution of an antenna is essentially unaffected by the distance to the antenna. The shape of an antenna's amplitude pattern changes as the distance of observation is adjusted from the reactive near field to the far field due to fluctuations in both the magnitude and phase of the fields. Figure 2.18. shows the typical evolution of an antenna's shape, with the largest dimension D.

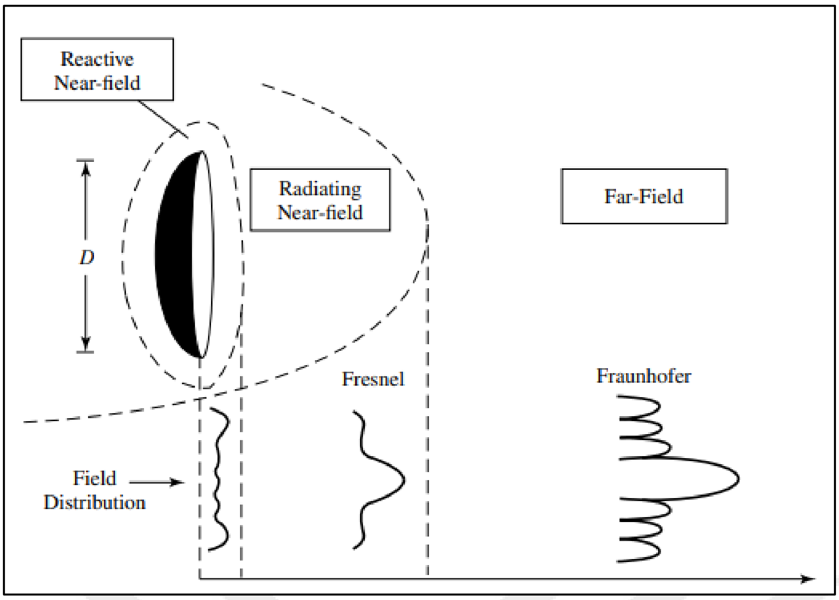


Figure 2.18. Antenna amplitude pattern shape on regions [6]

Radiation intensity is a far-field parameter defined as an antenna's power output per unit solid angle. It is expressed mathematically as defined in Eq. 2.4.

$$U=r^2\times W_{rad} \quad (2.4)$$

In this equation, U represents the radiation intensity and its unit is W/unit solid angle. W is radiation density and its unit is W/m^2.

2.7. Beamwidth

An antenna's beamwidth is a crucial measure of its merit and is frequently traded off against the side lobe level. The side lobe keeps growing as the beamwidth reduces. The beamwidth means the angular separation between two identical points of the maximum pattern on the opposite side. HPBW and First-Null Beamwidth (FNBW) can be given as examples. HPBW is defined by IEEE as “The angle between two directions where the radiation intensity is half of the beam's value is found in a plane that contains the direction of the beam's maximum.” FNBW means the angular separation between the first nulls of the pattern. Beamwidths with patterns that are -10 dB below the maximum or any other value are known as other beamwidths.

2.8. Directivity

Directivity is the ratio of the radiation intensity from the antenna in a specific direction to the average radiation intensity across all directions. If the direction is not specified, the direction of maximum radiation is implied. It is mathematically expressed as given in the Eq. 2.5.

$$D=\frac{U}{U_0}=\frac{4\pi U}{P_{rad}} \tag{2.5}$$

D = directivity (dimensionless)
U = radiation intensity (W/unit solid angle)
U_0 = radiation intensity of isotropic source (W/unit solid angle)
P_{rad} = total radiated power (W)

2.9. Gain and Radiation Efficiency of Antennas

The antenna's efficiency and directional capabilities are both taken into consideration by the gain, which is directly correlated with the directivity. This is calculated by dividing the total input power that the antenna accepts by 4π by the radiation intensity in a specific direction.

$$\text{Gain}=4\pi\frac{\text{radiation intensity}}{\text{total accepted input power}}=4\pi\frac{U}{P_{in}} \tag{2.6}$$

U = radiation intensity (W/unit solid angle)
P_{in} = Total accepted input power

2.10. Bandwidth

The range of frequencies within which the performance of the antenna is defined as bandwidth. Frequency affects a lot of antenna parameters. Directivity, gain, HPBW, and other parameters may change as a result of changes in the radiation pattern brought about by changes in frequency. Therefore, it is crucial to make sure that the appropriate parameters are selected when taking the antenna bandwidth into account.

2.11. Reflection Coefficient

The reflection coefficient expresses the ratio of the wave reflected from the input or output ports of a transmission line or an antenna. The reflection coefficient is described as shown in Eq. 2.7. In this equation, Z_{in} means the input impedance of the antenna, and Z_o means the characteristic impedance of the transmission line.

$$\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} \tag{2.7}$$

2.12. Standing Wave Ratio (SWR)

The standing wave ratio is the ratio of the reflected wave at the antenna ports to the transmitted wave. The standing wave ratio is a parameter that measures the efficiency and matching performance of an antenna. If the input impedance of the antenna and the characteristic impedance of the transmission line are not equal, reflections and standing waves occur. The standing wave ratio is calculated by Eq. 2.8.

$$\text{SWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{2.8}$$

2.13. Scattering parameters (S-Parameters)

S-parameters, also known as scattering parameters, represent a collection of measurements that characterize the electrical performance of linear electrical networks as they experience different signal reflections and transmissions. These parameters are crucial for the design and examination of RF and microwave circuits, including antennas, amplifiers, filters, and other high-frequency elements [10]. S-parameters measure the behavior of RF signals when they meet discontinuities or components within a transmission line. They indicate the extent to which the signal is reflected, transmitted through, or sent to other ports [15].

The scattering matrix of an N-port system is defined according to the incident ($[V^+]$) and reflected ($V^-]$) voltage waves in Eq. 2.9.

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

$$[V^-] = [S]\,[V^+] \tag{2.9}$$

A two-port system has four different S-parameters. These are called S_{11}, S_{21}, S_{12} and S_{22}.

Here,

- S_{11} = Input port voltage reflection coefficient,
- S_{21} = Forward voltage gain,
- S_{12} = Reverse voltage gain,
- S_{22} = Output port voltage reflection coefficient.

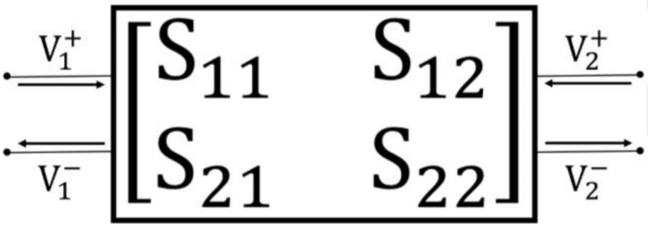


Figure 2.19. Scattering parameters [16]

Figure 2.19. shows the incoming/reflected waves and scattering parameters of a two-port system. The reflection coefficients of the input and output ports are shown in Eqs. 2.10 and 11 [16].

$$S_{11} = \frac{V_1^-}{V_1^+}\bigg|_{V_2^+ = 0} \tag{2.10}$$

$$S_{22} = \frac{V_2^-}{V_2^+}\bigg|_{V_1^+ = 0} \tag{2.11}$$

The two-port system's forward and reverse voltage gains are given in Eqs. 2.12 and 2.13 [16].

$$S_{21} = \frac{V_2^-}{V_1^+}\Bigg|_{V_2^+ = 0} \qquad (2.12)$$

$$S_{12} = \frac{V_1^-}{V_2^+}\Bigg|_{V_1^+ = 0} \qquad (2.13)$$

In this case, the reflection voltage waves of the system are expressed in Eqs. 2.14 and 2.15 [16].

$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+ \qquad (2.14)$$

$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+ \qquad (2.15)$$

2.14. Axial Ratio

Axial ratio (AR) is a critical parameter in antenna theory, especially relevant for circularly polarized antennas. It quantifies the degree of circular polarization of an electromagnetic wave, indicating how perfectly circular the polarization is. The axial ratio is the ratio of the major axis to the minor axis of the polarization ellipse formed by the electric field vector of an electromagnetic wave. The graphic of AR is shown in Figure 2.20. The calculation of AR is shown in Eq. 2.16 [6].

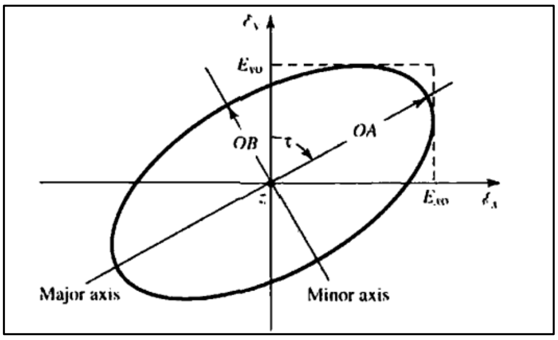


Figure 2.20. Axial ratio [6]

$$AR = \frac{OA}{OB} = \frac{\text{major axis}}{\text{minor axis}} \qquad (2.16)$$

For circular polarization, this ellipse is a perfect circle, where the major and minor axes are equal. The geometry and feeding method of the antenna plays a critical role in achieving the desired axial ratio. Imperfections in the manufacturing process can lead to deviations from the intended axial ratio. Environmental factors like multipath reflections and obstructions can affect the polarization and thus the axial ratio.

A lower axial ratio (closer to 1) indicates better circular polarization quality, which is crucial for applications like satellite communication where the orientation between the transmitter and receiver can change. A lower axial ratio reduces polarization mismatches and improves signal integrity and reception quality. Antennas designed for circular polarization aim for an axial ratio as close to 1 as possible to ensure consistent performance regardless of orientation.

In perfect circular polarization, the axial ratio is equal to 1 (0 dB). The electric field vector traces out a perfect circle as it propagates, indicating equal power in both orthogonal components of the wave. It is ideal for satellite communication and GPS, where the orientation of the receiving antenna relative to the transmitting antenna can vary.

In elliptical polarization, the axial ratio is greater than 1 (> 0 dB). The electric field vector traces out an ellipse, indicating unequal power distribution in the orthogonal components. The wave is not perfectly circularly polarized.

In linear polarization, the axial ratio approaches infinity. The electric field vector oscillates along a straight line, with one of the axes of the ellipse shrinking to zero.

The axial ratio is measured using:
•Vector Network Analyzers (VNAs): Can measure the S-parameters of the antenna, from which the polarization and axial ratio can be derived.
•Antenna Test Ranges: Involves rotating a linearly polarized receiving antenna and measuring the received signal strength at different orientations.

Axial ratio is a vital parameter for assessing and designing circularly polarized antennas. Achieving a low axial ratio ensures high-quality circular polarization, which is essential for applications where the orientation between transmitting and receiving antennas is variable.

Understanding and optimizing the axial ratio helps improve signal integrity and overall system performance.

2.15. The Transmission Lines

Different kinds of wires and cables which are called transmission lines help send signals, like talking or pictures, from one place to another. Some of these are called two-wire lines, coaxial cables, microstrips, strip lines, coplanar waveguides, and waveguides. When we look at these transmission lines, we check things like how well they work, how much they cost, how much they can carry, and how much energy they might lose while sending signals. Figure 2.21. shows the most popular transmission lines.

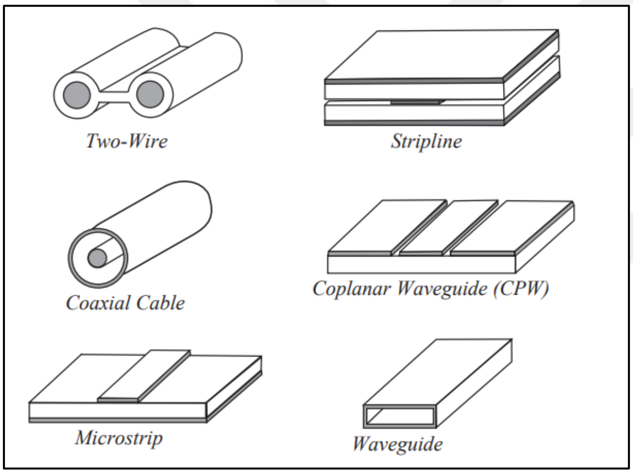


Figure 2.21. Transmission lines

2.15.1. Two-wire transmission lines

Two-wire transmission line includes two separate wires and a medium. The medium has a permittivity and it is called as ε. It is shown in Figure 2.22. The distance between the two wires is D and their diameter is d.

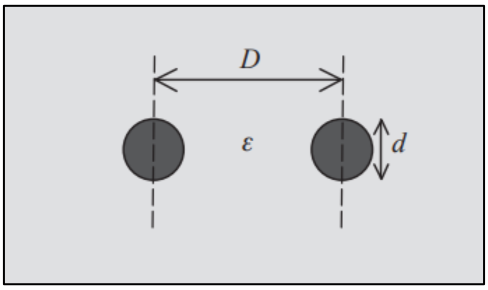


Figure 2.22. The Two-wire transmission line

A common type of wire used for connecting TV antennas to TVs was called a 300-Ω line. This kind of wire was often used a long time ago to help the TV get signals from the antenna. When we use two wires to send signals, a lot of the energy can get lost in the air, especially when we try to send really fast signals. Because of this, these two-wire lines aren't good for sending fast signals. They work best for sending signals that are slower, usually less than 300 MHz.

2.15.2. Coaxial cable

The coaxial cable consists of a central, insulated wire mounted inside a tubular outer conductor. The inner conductor is insulated from the outer conductor by insulating materials. These materials have to have good insulating characteristics and low dielectric losses at high frequencies over a wide range of temperatures. In arrange to guarantee great Electromagnetic Compatibility (EMC) execution, protected and double-shielded coaxial cables have been created and are accessible on the advertise. This sort of transmission line is broadly utilized for RF building and radio wire estimations and for the association between the radio wire and handset. Its characteristic impedance as an industrial standard is nearly 50 Ω or 75 Ω.

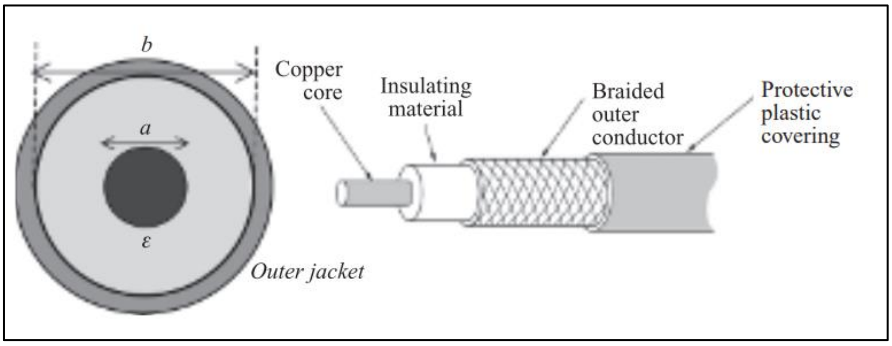


Figure 2.23. The coaxial cable

2.15.3. Microstrip line

A microstrip line may be seen as a subordinate of a two-wire transmission line and is maybe the foremost broadly utilized shape of the planar transmission line. One side of the structure is freely accessible for the mounting of bundled gadgets and the geometry lends itself amazingly well to printed circuit board designing strategies to characterize the circuit. It has been utilized broadly in microwave and millimeter circuits and frameworks.

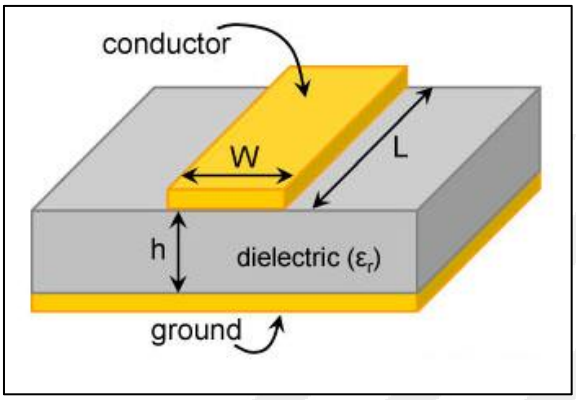


Figure 2.24. Microstripline

2.16. The Input Impedance

The calculation from the terminals of the antenna calls as input impedance. It is calculated by the ratio of the voltage to current at a pair of terminals. For a better understanding, Figure 2.25. shows an antenna schematic. The impedance value mentioned here is the resistance value between points a and b and is calculated by the voltage ratio to the current between these two points.

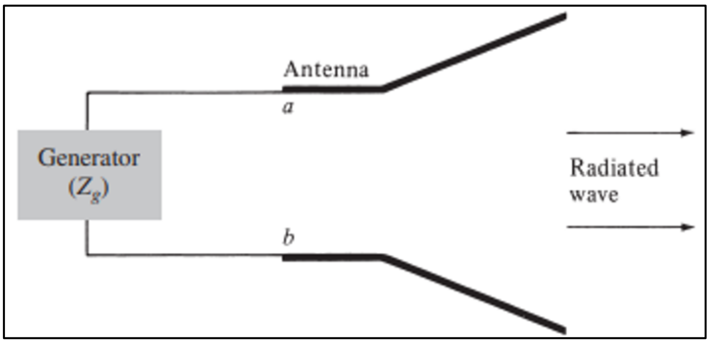


Figure 2.25. Antenna in transmitting mode [6]

Figure 2.26. is the Thevenin equivalent circuit of this antenna scheme calculated with appropriate metrics. Figure 2.27. is the Norton equivalent circuit.

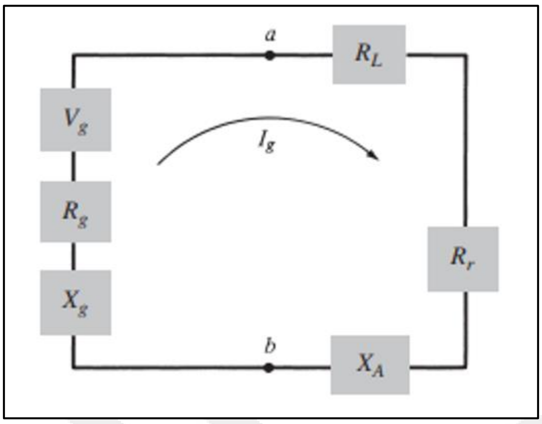


Figure 2.26. Thevenin equivalent circuit of the antenna [6]

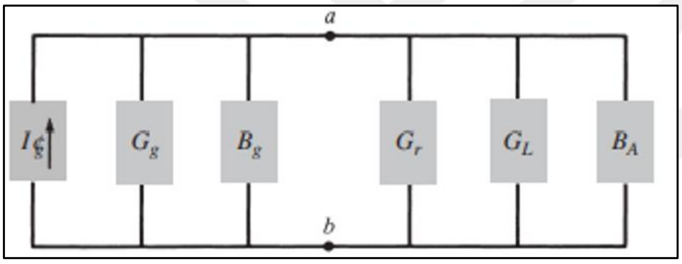


Figure 2.27. Norton equivalent circuit of the antenna [6]

As seen in Figure 2.26, the impedance of the antenna is obtained by the sum of the values of R_L , R_r and X_A. R_r is the radiation resistance of the antenna and R_L is the loss resistance of the antenna, and X_A is the antenna reactance at terminals a–b.

The input impedance of an antenna is usually a function of frequency. Therefore, the antenna matches the connected transmission line and other related equipment within only one bandwidth. In addition, the input impedance of the antenna depends on many factors including its geometry and its proximity to surrounding objects. Because of their complex geometries, only a limited number of practical antennas have been investigated analytically. For many others, the input impedance has been determined experimentally. Antenna impedance is usually measured using specialized equipment like an antenna analyzer or a network analyzer.

To minimize the losses on the antenna resistance and thus increase the antenna efficiency, the characteristic impedance of the transmission line feeding the antenna should be selected as the reciprocal of the antenna impedance. This process is called impedance matching. The resistance of a half-wave dipole antenna is approximately 75 Ω. If the feed of this antenna is made with a 75 Ω coaxial cable, impedance matching is achieved.

3. CROSS-DIPOLE (TURNSTILE) ANTENNA

Cross-dipole antennas have been widely developed for current and future wireless communication systems [5]. Cross-dipole or Turnstile antennas are special tools that help send out radio signals in all directions, kind of like how a big flashlight shines light everywhere. They are mostly used for things like TV and radio broadcasting. These antennas are made from parts that look like two flat sticks crossed in the middle, and they are set up flat, like a big "X" lying on the ground. They work by using electricity in a way that makes the signals spread out evenly all around. This helps everyone nearby to catch the same radio or TV signals no matter where they are standing [17].

Turnstile antennas are utilized for broadcast transmitters that require an omnidirectional radiation pattern with horizontal polarization, primarily in the VHF and UHF ranges. Typically, they are accomplished in the horizontal plane using standard folded or cross-dipoles. These are fed either with so-called batwing radiating elements or currents of the same intensity and in phase quadrature. In this way, an omnidirectional radiation pattern is produced [18, 19].

3.1. The History of Cross-Dipole (Turnstile) Antenna

A cross-dipole is a type of antenna that helps send and receive radio signals, and it's been around for a long time since the 1930s. The first one was created by a person named Brown, and it was called a "turnstile antenna." In the 1940s, people made a better version called the "superturnstile" that could pick up more types of signals. Then, in 1961, they made a new kind of cross-dipole that worked a little differently and could handle signals that went in circles. In the 2000s, they improved it even more by using two separate connections that worked together to send and receive signals in different ways [5].

The first cross-dipole antenna was developed with an emphasis on a new ultrahigh-frequency radiating system that economized energy by concentrating it in the horizontal plane equally in all directions [5]. This antenna is made up of two pieces that look like sticks, placed at a right angle to each other, and they work together to send out signals. Since that first design, people have made different versions of this antenna that can do even more things, like work better over a wider range of signals, be smaller, and be easier to make.

3.2. The Advantages and Sidadvantages of Cross-Dipole (Turnstile) Antenna

Two indistinguishable half-wave dipoles are set at the right points to each other and are bolstered in phase. These dipoles are energized 90° out of stage with each other. Entryway clusters can also be named as cross-dipole clusters. To provide high directivity, several turnstiles may be stacked along a vertical axis, and are phased as shown in the figure given above. The polarization of these turnstile antennas depends upon their mode of operation [20].

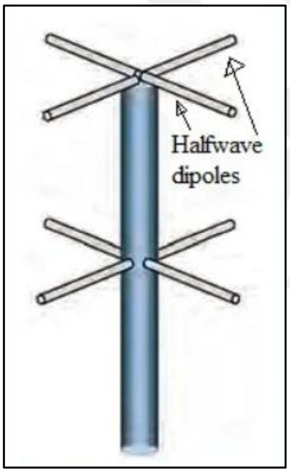


Figure 3.1. Double Turnstile antenna

The advantages of turnstile antenna are;

- It offers higher gain when multiple turnstile antennas are stacked together.
- Super-turnstile produces high-gain output.
- Better directivity is achieved.
- It is simple to construct as it uses two linear dipoles.

The disadvantages are;

- The radiation power is 3dB below the maximum radiation of a half-wave dipole radiating the same power.
- It offers poor near-the-horizon performance.
- It offers high image quality in the +/-30º field of view about vertical [21].

The applications are;

- VHF communications
- FM and TV broadcasting
- Military communications
- Satellite communications

3.3. The Telemetry Systems

The process of monitoring or controlling a system or facility remotely via cable or wireless is called telemetry. In general, when we say telemetry, we mean wireless communication [22]. The terrain does not have to be flat in places where wireless telemetry systems are used; even if there are elements that prevent communication between antennas such as mountains, hills, etc., such obstacles can be overcome with RF modems with router features. The distance between the points where communication will be provided can be kilometers. Today it is possible to communicate with RF modem systems between distances of hundreds of kilometers [23].

Telemetry systems are used in many areas such as wildlife observation, medical and military applications, spacecraft monitoring, and unmanned aerial and ground vehicles monitoring and control. The antenna I will design will serve as a telemetry antenna on a ground platform. When determining the size and frequency range of the antenna, it is very important for what purpose and on which platform the antenna will be used. When deciding on the dimensions, a literature review was conducted, and systems that previously used telemetries were used.

- David Aguirre Salcedo, Juan Pablo Ciafardini, and Jose Alberto Bava (2020) used a telemetry system to increase the radio link contact time of telemetry and telecommand data of low orbit satellites based on the data relay systems through Inmarsat-F4 GEO satellites constellation [24].
- Royer, F. & Lutcavage, M. (2008) used a telemetry system to track marine organisms with a satellite communication system and determine their locations. The main purpose of this study is to prove that the system they developed provides more accurate results in finding the location compared to the old systems. They managed to transfer the location information they obtained with the telemetry system to the observer

simultaneously and thus they were able to see that the system they developed provided more accurate results [25].

- Çubuk, M. (2009) used the telemetry system in medical networks in his study. Thanks to the telemetry system, he measured the temperature, position, pressure, humidity, density, pulse rate, etc., of the patients and transferred the measurement results to the administrative units. The telemetry system he used provides 4 communication via RF [26].
- Altemose, G et al. (2011) used the telemetry system to monitor and control the operating status of lithium-ion batteries to be used in satellite systems. The communication of the telemetry was carried out via satellite [27]
- Larrauri, J. I et al. (2013) designed a telemetry system to be used in overhead power line inspection using unmanned aerial vehicles. RS232 serial communication port was used in the telemetry. Data communication was carried out via GPS [28]
- Mammadov, E. & Gueaieb, W. (2014) designed a telemetry system to be used in unmanned aerial vehicles. The telemetry system they designed was used to transmit the photographs taken by the unmanned aerial vehicle from the sky to another point [29].
- In their study, Duchrow, T and his colleagues (2012) provided the data collection process using the CAN network. The data received from the CAN network was transferred to the central station via a telemetry system. In their study, the communication of the telemetry system was provided using the GPRS system [30].

3.4. The Literature Review

Literature research has been conducted on the general features of the antenna to be made and how we will feed this antenna. The first part of this study discusses studies on how to feed. It is commonly known that when the radiation patterns of transmitting and receiving antennas are circular polarized (CP), they become less sensitive to their respective orientations. This makes the CP antennas ideal for use with a variety of wireless systems, including telemetry systems, radio frequency identification (RFID), and the Global Positioning System (GPS). To perform circular polarization, it was decided to create an asymmetric dipole structure. For the feeding of these dipoles, a reference was taken from an article published in 2009. This article [31] mentions the antenna feedings made for circular polarization. The antenna in question in the article includes a cross-dipole antenna obtained from dipole antennas formed in the form of a bowtie. This article divides circularly polarized antennas into two categories. These categories are stated as single-fed and dual-fed. In single-fed feeding, the feeding is obtained without creating any phase difference. In the dual-fed structure, circular polarization can be generated by exciting two orthogonal resonant modes that have equal amplitude and 90º phase differences. It was decided to use a coaxial cable to create this phase difference. Two vertical dipole arms were touched to the inner part of the coaxial cable and the other two vertical arms were touched to the outer part of the cable. It is aimed to create a 90º phase difference by grounding the outer part of the coaxial cable with the help of a transmission line to be added below. A similar feeding structure was also encountered in the article mentioned in [32]. In this article, unlike [31] and this thesis, dipoles of equal length at halfwave length were used, but again, feeding with a 90º phase difference was created using the dual-fed structure to create circular polarization. While the dual-fed structure was being investigated, research was also conducted on single-fed feed structures. The articles [33] and [34] were taken as references on this subject. These articles mention circularly polarized micropatch antennas established with a single-fed feed structure.

Another article read mentions the differences in dipole lengths [35]. This article describes an antenna made of dipoles of different lengths and geometry on a printed circuit board. The article mentions that dipoles of different lengths can achieve multiple resonances, each dipole arm is divided into four branches with different lengths.

4. PROPOSED CROSS-DIPOLE ANTENNA GEOMETRY AND DESIGN

In this section, how the telemetry antenna to be described in the thesis was designed will be discussed. The structure and properties of the antenna and the effect of these properties on the antenna radiation are explained. To decide on the design of the antenna, we must first determine what our needs are. Our aim is to design a cross-dipole antenna that will provide circular polarization in the S-band frequency range. Turnstile antennas have been used for space applications [36, 37]. Its major advantages include low mass and wide-angle beams for larger earth coverage [38].

An antenna is one of the principal parts of the satellite correspondence framework which sets up a connection between satellite subsystems and the Earth station [39]. The characteristics of the designed antenna have been determined according to its intended function. It is desired that the antenna operates at the frequency range between 2060-2230 MHz which defines the S-band. At the same time, the antenna should have circular polarization.

An important area of study in antenna engineering is the design of circular polarized antennas. This is caused by the superior propagation of CP structures in addition to other alluring attributes like decreased sensitivity to the angle of orientation between the transmitter and the receiver and a decrease in multipath effects [40]. A thorough explanation of CP excitation methods is provided [41].

This thesis will be conducted for S-band by taking the 2060-2230 MHz range as a reference. Therefore, we will design the antenna with appropriate values in this range. All improvements will be made to provide these values. While providing these values, we also expect the antenna to radiate in a circular polarization. Table 4.1. shows the targeted antenna parameters.

Table 4.1. Targeted measures

	Operating frequency	AR	HPBW	Main lobe direction	Magnitude of S_{11}
Targeted Measures	2060-2230 MHz	≤ 3 dB	65-75 º	0±5º	≤ 10 dB

Figure 4.1. shows the overall geometry of the antenna. This figure was drawn using the CST program. High-performance 3D electromagnetic analysis software, CST Studio Suite®, designs, analyzes, and optimizes electromagnetic (EM) systems and components. The CST Studio Suite has a single-user interface that houses electromagnetic field solvers for electromagnetic spectrum applications. The figure shows that the antenna consists of a dipole section, a reflector structure, and a transmission line. The dipole structure at the top is connected via a coaxial cable. The same cable passes through the center of the reflector and is connected to the transmission line.

The parts in this antenna are designed to work in the desired frequency range by changing certain values. The dipole arms are asymmetric. This asymmetry is made in this way to provide circular polarization. The reflector has a cylindrical but flat structure. The aim is to increase the radiation in the radiation diagram by adjusting the distance of this reflector. The angle that the dipole arm makes with the reflector will be used to adjust the axial ratio of the antenna and the radiation diagram. Detailed information about the sections is given in the subsections.

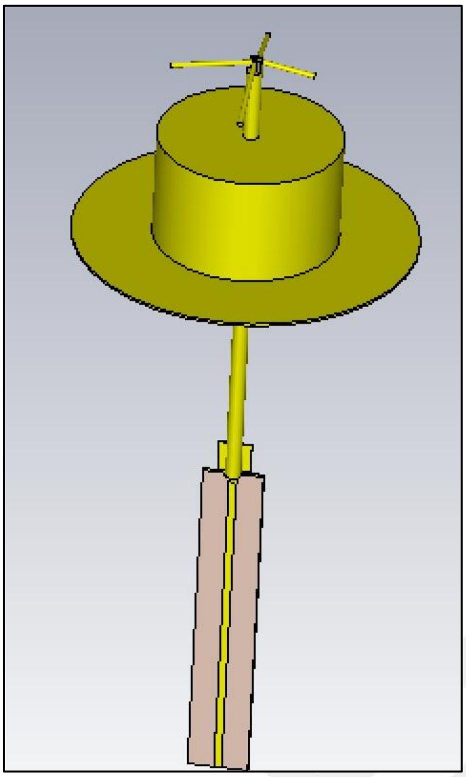


Figure 4.1. Designed antenna

Figure 4.2. shows the designed antenna’s geometry and its components’ dimensions.

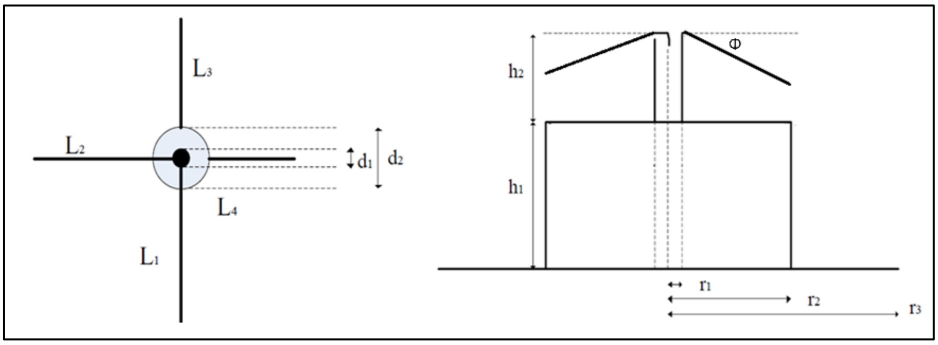


Figure 4.2. The geometry of the antenna

4.1. The Structure of Cross-Dipole

The cross-dipole is a common type of modern antenna with a radio frequency (RF)- to mm-wave frequency range [5]. In this design, a cross-dipole structure is located at the top of the antenna. The lengths of all dipole elements in the antenna are different. This dipole is called an asymmetric cross-dipole. For circular polarization, the method of adjusting the cross-dipole arm lengths is adopted. Asymmetrical arms of different lengths create circular polarization. The values determined for the initial design of the antenna are shown in Table 4.2. Dipole lengths according to the structure are shown in Figure 4.3. All dipole arms have the same diameter, which is 2 mm. The longest arm is 35 mm and the shortest arm is 20 mm. The other two arms are 30.5 mm and 26 mm.

Table 4.2. Dipole lengths

Parameters	Value (mm)
L1	35
L2	30.5
L3	26
L4	20

The dipole structure is shown in Figure 4.3. The cross-dipole arms have been bent with an angle (Φ) in order to tune the axial ratio (AR) and radiation pattern. The lengths of the dipoles and their angles are parameters that can be changed in the antenna design. By adjusting these parameters, an optimal radiation at the specified frequency will be found.

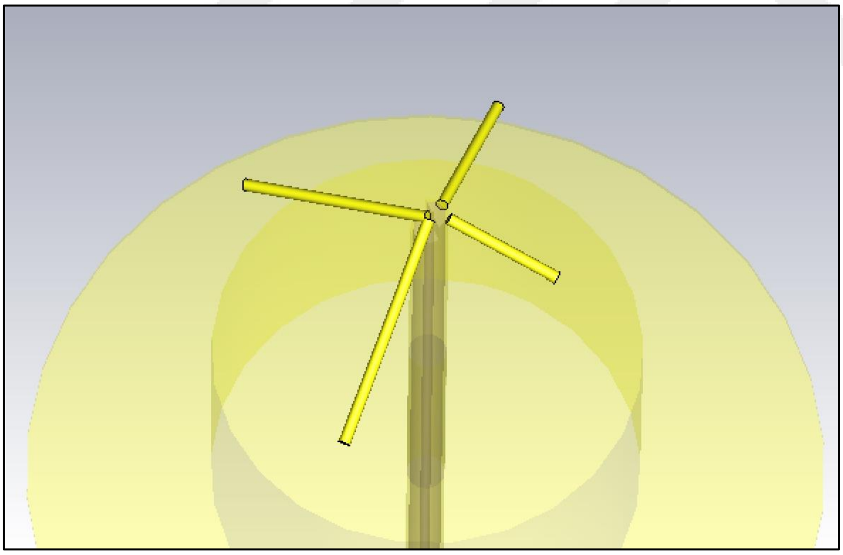


Figure 4.3. The structure of cross-dipole

Material selection has a significant impact on the performance of the antenna. Because the material's conductivity, reflection loss, and other electrical properties affect the efficiency and characteristics of the antenna. The material of all dipoles is selected as copper (pure) on CST simulation.

The dipoles are connected via coaxial cable. This cable is positioned between the dipoles and the feed line, and its length and diameter have been kept constant in all analyses. The whole cable is shown in Figure 4.4.

The coaxial cable used in this antenna is 131 mm long. In the simulation, this coaxial cable is first drawn and the coaxial cable is centered, that is, its middle is taken as the center. The alignment of the reflector is also done at this center.

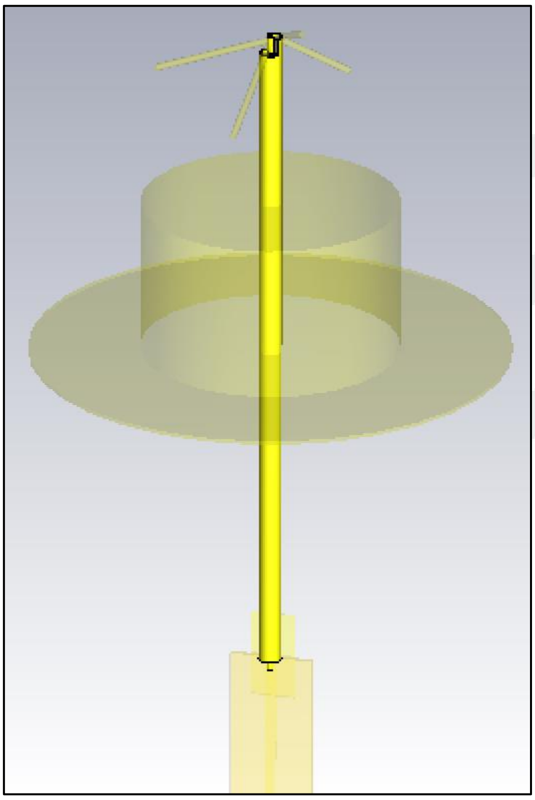


Figure 4.4. Coaxial cable

Coaxial cable has 3 parts which are inner, dielectric, and outer. The inner and outer parts are selected as copper (pure), and the dielectric part is chosen as PTFE (lossy) on CST simulation. Figıre 4.5. shows the upper part of the coaxial cable. The internal structure of the cable can be seen more clearly. Two dipoles touch the inner part, while the other two touch the outer part. The ground part coming from the antenna’s feed line is in contact with the outer part of the cable. Therefore, the dipoles that touch the outer part of the cable also have a ground structure.

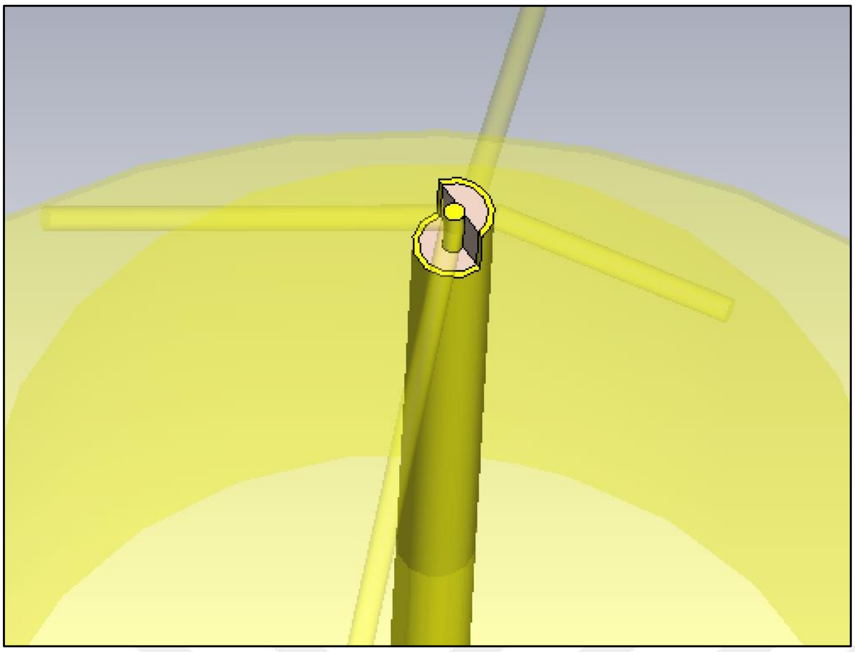


Figure 4.5. The top of cable

4.2. The Structure of Reflector

A reflector is a conducting surface or element placed near an antenna element to direct the radio waves emitted by the antenna in a desired direction. The primary purpose of a reflector is to increase the antenna's gain and improve its directionality by reflecting electromagnetic waves [3]. Reflectors work based on the principles of reflection and interference. When an electromagnetic wave strikes a conducting surface, it is reflected. Reflectors redirect the waves in a specific direction, aligning them to constructively interfere and enhance the signal in the desired direction [10]. By placing the reflector at a precise distance from the active element, the reflected waves combine with the direct waves from the antenna element. This constructive interference increases the overall signal strength in the desired direction, known as the main lobe [42]. The angle of incidence equals the angle of reflection. In applications like satellite communication, radar, and broadcasting, reflectors improve the overall performance and reliability of the antenna system [43].

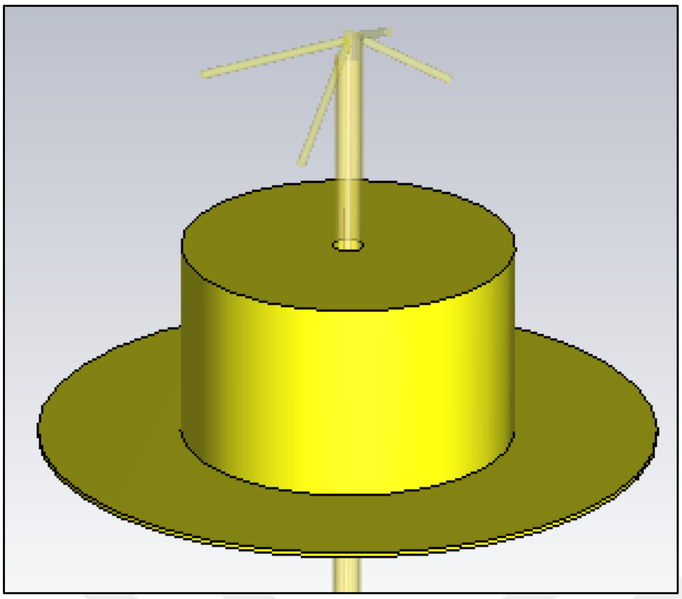


Figure 4.6. Reflector

The reflector structure used in this design is shown in Figure 4.6. The reflector is formed by the combination of two cylindrical structures. The height of the first cylinder is 1 mm, and its radius is 65 mm. It is located below the reflector structure. The height of the second cylinder is 42 mm, and its radius is 35 mm. A coaxial cable passes through the center of the two cylinders. The outer structure of the coaxial cable is grounded. Since this ground structure, the reflector is also grounded. This structure of the reflector is called defected ground structure. Defected ground structure is a periodic or aperiodic stepwise configuration fault that occurs in the ground of a planar transmission line, and this fault disrupts the shield current distribution in the ground plane due to the defect in the ground [44].

In this design, the lengths of the reflectors are consistent in each analysis. The distance of the reflector to the cross-dipole is variable. The material of the reflector is selected as copper (pure) on the CST simulation.

4.3. The Structure of the Transmission Line

Transmission lines are critical components in antenna systems, playing an important role in signal transmission, impedance matching, and overall system performance. In this design, a feeding structure has been established with a microstrip line located underneath the coaxial cable. Microstrip line consisting of a conductor strip on a dielectric substrate, with a ground plane on the opposite side. The structure is shown in Figure 4.7.

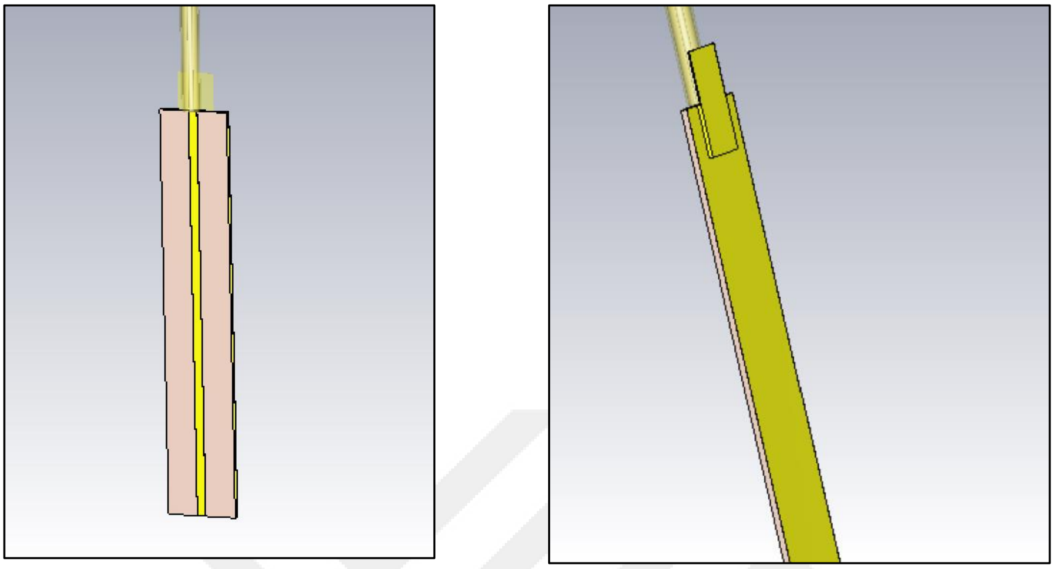
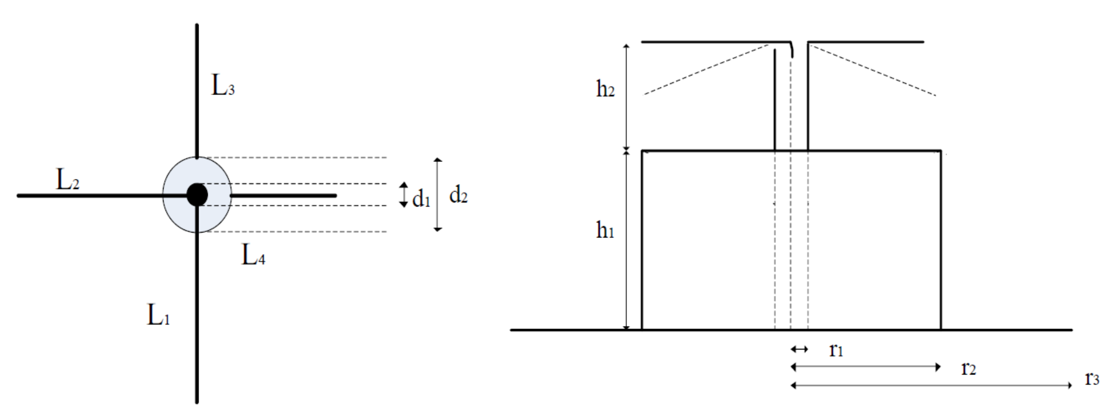


Figure 4.7. Transmission line

5. SIMULATION RESULTS

At the beginning of the simulation process, drawings on CST were made based on the parameters specified in Table 5.1. and the geometry detailed in Section 4. All dipole arms have the same diameter, which is 2 mm. The longest arm is 35 mm, and the shortest arm is 20 mm. The other two arms are 30.5 mm and 26 mm. The coaxial cable is 131 mm long. There are two reflectors in the middle. The biggest cylinder is 1 mm height, and its radius is 65 mm. The second cylinder is 42 mm in height, and its radius is 35 mm. A coaxial cable passes through the center of the two cylinders. The size of the cylinders will not be changed at all in the simulation. Only the distance of these reflectors to the dipoles is changed.

Table 5.1. Antenna parameters



Parameters	Value (mm)
L1, L2, L3, L4	35, 30.5, 26, 20
h1, h2	42, 23.5
r1, r2, r3	3.12, 35, 65

The analysis has altered the distance between the dipoles and the reflector and the angles of the dipoles relative to the plane. Furthermore, geometries where a certain proportion extended the lengths of the dipoles have also been analyzed.

The designed antenna is intended to operate in the S-band. The S-band is defined as between 2060-2230 MHz. Thus, the frequency range chosen for analysis is 1.7- 2.5 GHz. The far-field analyses were made in the 1.7 to 2.5 GHz range at every 0.1 GHz frequency interval. We aim for the S-parameter of the antenna to be below -10 dB in the 2060-2230 MHz range and for the axial ratio value of the antenna to be 3 dB or less in the S-band range. In addition, the Half Power Beamwidth, which is the value at the point where the power drops by 3 dB, in the radiation diagrams of the antenna in this range should be in the range of 65-75. All analyses of the antenna will be made in this S-Band range. The center frequency of our antenna, which will operate in the 2060-2230 MHz range, is 2145 MHz. We design our analyses so that the antenna will operate best in this range but at the 2145 MHz center frequency.

After designing the antenna, analyses were conducted for approximately 100 different scenarios. For each analysis, the S-parameter, axial ratio, and radiation pattern within the specified frequency range were examined. The analyses were divided into three categories: angle changes, length changes, and reflector distance changes. Based on the results of these three categories of analysis, the main antenna parameters will be determined and evaluated.

The reason for dividing the simulations into 3 different topics is that we want to see which changes affect which parameters of the antenna. In the following sections, the simulation results selected for each change and their effects will be discussed.

5.1. Analysis-1: Angle

The analyses were performed by varying the dipole angles. The length of dipoles and the distance to the reflector are the same in all analyses. Table 5.2. below lists the parameters that were changed during Analysis-1.

The Run ID section in the table indicates the simulation number. In this analysis, only the angle of the dipole with the plane has been changed. All other values have been kept constant. The lengths of the dipoles are still 35 mm, 30.5 mm, 26 mm, and 20 mm as in the first case. The reflector volumes and coaxial cable lengths have also been kept constant. The distance of the reflector to the dipoles has also been kept constant and this value has been determined as 55 mm. The reflectors have been moved in all analyses by taking the middle of the coaxial cable as a reference. The center point of the analyses is the center point of the cable.

Table 5.2. Analysis-1 parameters

Run ID	Dipole Angle (º)	Reflector distance to dipoles (mm)
65	10	55
66	15	55
67	17	55
68	20	55

The S-parameter graph for Analysis-1 is shown in Figure 5.1. and the axial ratio (AR) is shown in Figure 5.2.

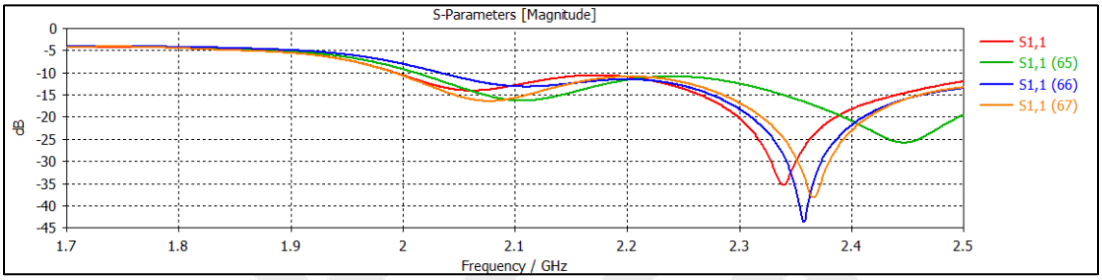


Figure 5.1. Analysis-1 S-parameters

Upon examining the figures, it is observed that the operating frequency of the antenna is around 2.3 GHz. When examining the current geometry, it is observed that changes in the angles of the dipoles affect the sharpness of the dip in the S-parameter. Run ID 66 shows the ideal results for this geometry. In simulation 66, the AR value is closest to 0 at around 2.3 GHz, indicating that circular polarization is optimized at this frequency. The axial ratio is shown in dB on this chart.

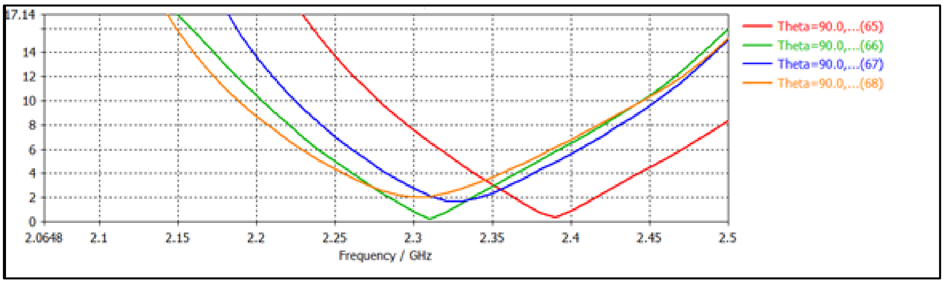


Figure 5.2. Analysis-1 axial ratio

The desired radiation range for the antenna is within the S-band, specifically from 2060-2230 MHz. As illustrated in the figures, none of the analyses with the varied parameters achieved the desired frequency range.

5.2. Analysis-2: Reflector Distance

In Analysis-2, analyses were made on different reflector distances. The Table 5.3. shows the parameters that were changed during Analysis-2. The Run ID section in the table shows the simulation number. In this analysis, only the distance of the reflector to the dipoles has been changed. All other values have been kept constant. The lengths of the dipoles are still 35 mm, 30.5 mm, 26 mm, and 20 mm as in the first case. The reflector volumes and coaxial cable lengths have also been kept constant. The dipole angles are kept constant at 17º.

Table 5.3. Analysis 2 parameters

Run ID	Dipole Angle (º)	Reflector distance (mm)
67	17	55
69	17	60.5
70	17	65.5

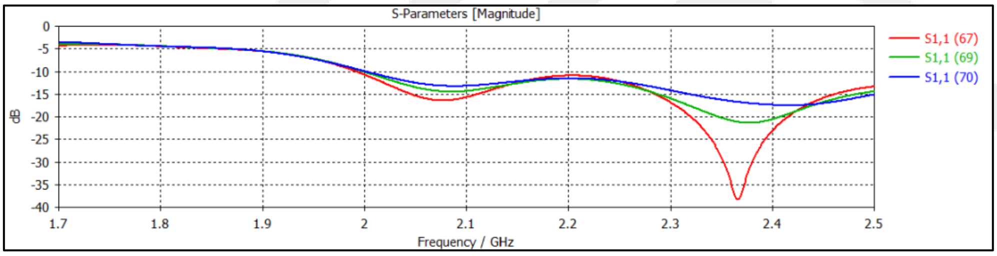


Figure 5.3. Analysis-2 S-parameters

Figure 5.3. and Figure 5.4. show the results. It appears that the changes made in Analysis-2 did not result in significant alterations to the axial ratio. The optimum scenario is 67 for Analysis-2.

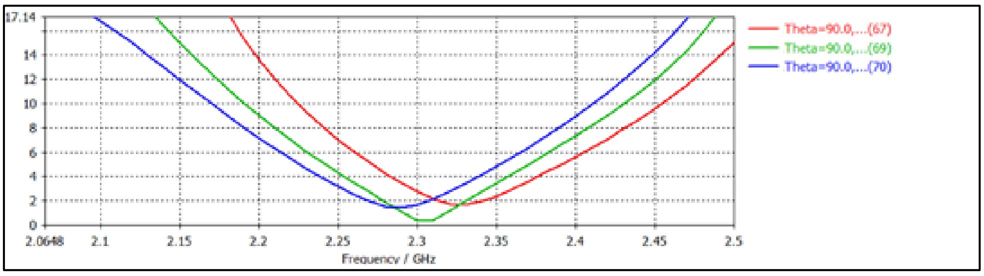


Figure 5.4. Analysis-2 axial ratio

The desired radiation range for the antenna is within the S-band, specifically from 2060-2230 MHz. As illustrated in the figures, none of the analyses with the varied parameters achieved the desired frequency range.

5.3. Analysis-3: The Lengths of Dipoles

In Analysis-3, analyses were performed by changing the lengths of the dipoles. In each analysis, the lengths of the dipoles were extended at the same rate, and lengths at different rates were analyzed. Table 5.4. shows the parameters that were changed during Analysis-3. The Run ID section in the table shows the simulation number. In this analysis, only the lengths of the dipoles were changed. All other values were kept constant. The reflector volumes and coaxial cable lengths were also kept constant. The dipole angles were kept constant at 20º. The distance from the reflector to the dipoles was kept constant at 65.5 mm. The extension rate and new lengths of the dipoles are given in the table below.

Table 5.4. Analysis-3 parameters

Run ID	L1 (mm)	L2 (mm)	L3 (mm)	L4 (mm)
55	35	30.5	26	20
54	37.10	32.33	27.56	21.20
61	38.5	33.55	28.6	22
28	39.935	34.8005	29.666	22.82

As shown in Figure 5.5. the lengths of dipoles affects the operating frequency of the antenna.

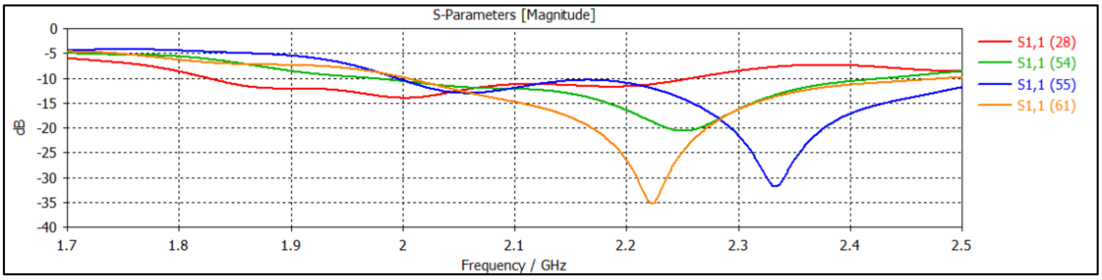


Figure 5.5. Analysis-3 S-parameters

After three main analyses made with three different changes, it was seen that the desired values could not be achieved. This forced us to make an optimization by changing not one but more than one parameter while performing our main analysis.

5.4. The Main Analysis

Within the scope of this thesis study, numerous simulations have been conducted on the antenna design depicted in the geometry. All simulations have been thoroughly analyzed across all parameters. As a result, the antenna selected as the most optimized solution will be discussed in this section. Table 5.5. shows the optimized parameters of the design.

Table 5.5. Main analysis parameters

Dipole Angle (º)	Reflector Distance (mm)	L1 (mm)	L2 (mm)	L3(mm)	L4 (mm)
20.11	65.5	38.5	33.55	28.6	22

The desired radiation range for the antenna is within the S-band, specifically from 2060-2230 MHz. Figure 5.6. shows that the antenna maintains attenuation below -15 dB across the entire band. The lowest point is at 2.2 GHz with a value of -56 dB. At 2.14 GHz, as shown in the figure, the value is -17 dB.

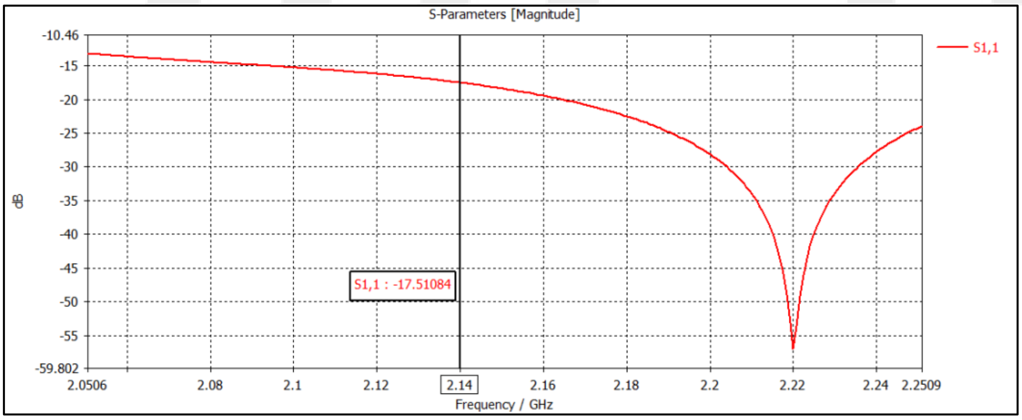


Figure 5.6. S-Parameters of the main analysis

Similarly, the axial ratio remains within suitable values across the band, as depicted in Figure 5.7. At the expected operating frequency of 2.14 GHz, the axial ratio of the antenna is 0.4. This value represents the point where the antenna exhibits its lowest axial ratio. Therefore, we can say that circular polarization is optimal at this point.

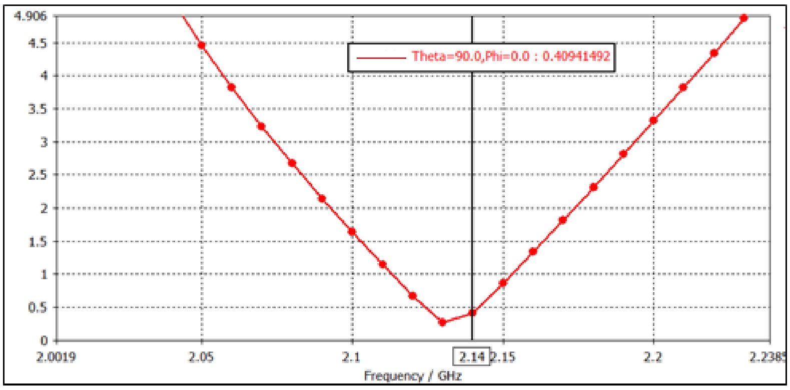
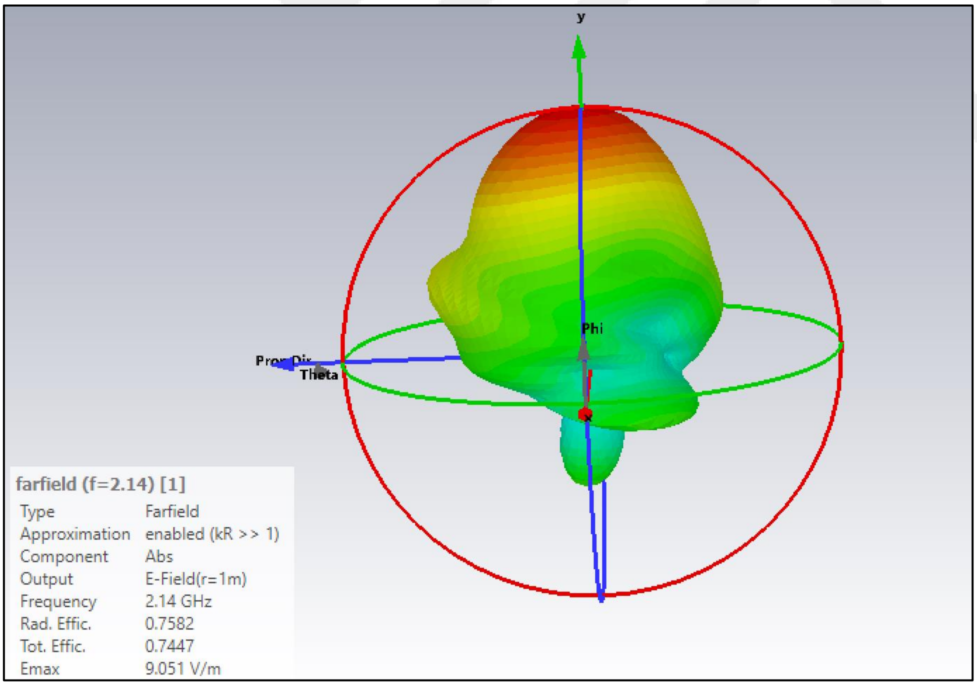


Figure 5.7. AR of the main analysis

The far-field analyses were made in the 1.7 to 2.5 GHz range at every 0.1 GHz frequency interval. Figure 5.8. shows the 3D radiation Pattern of the designed antenna. The main lobe and back lobe are shown clearly in this figure. The radiation is minimal around the reflector and reaches its highest level at the upper part where the dipoles are located.



farfield (f=2.14) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	E-Field(r=1m)
Frequency	2.14 GHz
Rad. Effic.	0.7582
Tot. Effic.	0.7447
Emax	9.051 V/m

Figure 5.8. Radiation pattern at 2.14 GHz – 3D

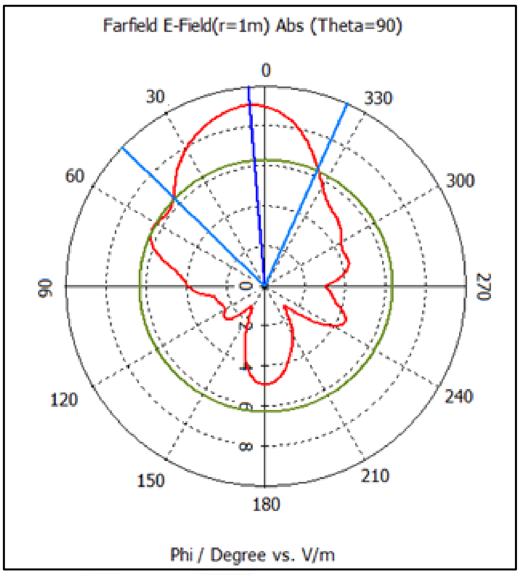


Figure 5.9. Radiation pattern at 2.14 GHz – 2D

Figure 5.9. shows the radiation pattern 2D. This radiation pattern corresponds to the value at 2.14 GHz. Considering the antenna's geometry, 0º corresponds to the dipole sections of the antenna. The direction of the main lobe is indicated by the dark blue line at 5º in the figure. The main lobe of the antenna has a value of 9.05 V/m. The V/m unit measures the strength of the electric field of the electromagnetic wave. The value given in V/m in a certain direction of an antenna's radiation pattern represents the electric field strength measured in that direction.

The angle formed by the antenna's primary beam and the horizontal plane is known as the antenna tilt. It can have both positive and negative values and is measured in degrees. Positive values mean that the beam is directed downwards, the procedure is called downtilting and the tilt value is referred to as downtilt. Negative values mean that the beam is directed upwards, the procedure is uptilting and the tilt value becomes uptilt [45]. The tilt angle, θ is approximately equal to ±5º. The antenna parameters are defined in Table 5.6.

Table 5.6. Radiation parameters

Main Lobe Magnitude	9.05 V/m
Main Lobe Direction	5º (deg.)
HPBW (3 dB)	70º (deg.)
Tilt angle	±5º

5.5. The Measurement Results

After the analysis, the antenna design was made real to ensure the accuracy of the analysis results. We made the antenna using the parameters determined in the study. The antenna was connected to the network analyzer and the S-parameter was measured.

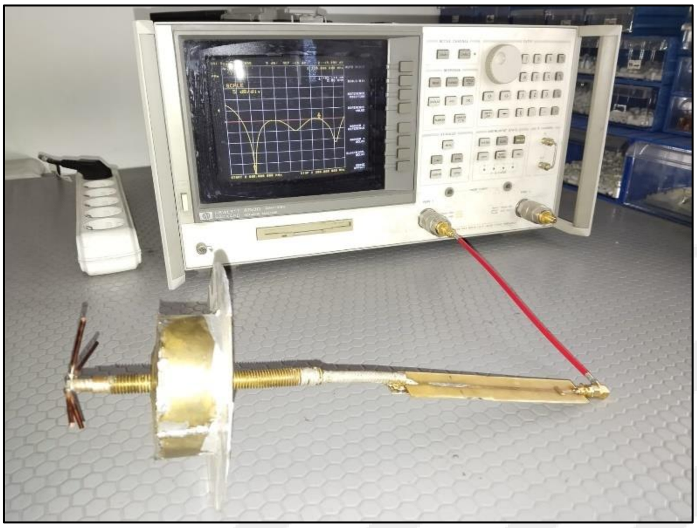


Figure 5.10. Prototyped antenna with Network Analyzer

Figure 5.10. shows the antenna connected to the network analyzer. The S-parameter of the antenna connected to the lower feed point is measured this way. In this figure, all parts of the antenna are visible. The screw structure on the coaxial cable is used to adjust the reflector of the antenna as desired.

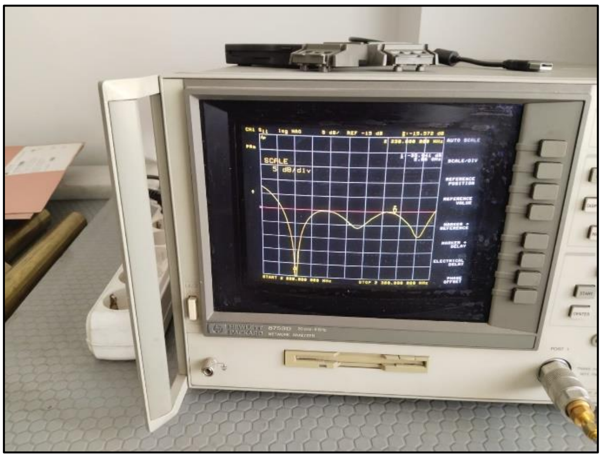


Figure 5.11. The measurement S-parameter

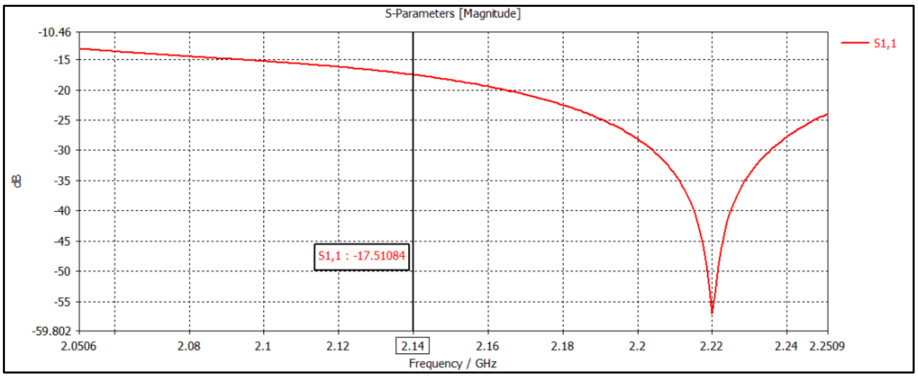


Figure 5.12. The simulation S-parameter

Figure 5.11. shows the measurement result on the Network Analyzer. Figure 5.12. shows the simulation results. When the two graphs are compared, it is seen that the measurement results of the antenna are as expected. The curve in the simulation and the curve in the measurement show the same thing. The antenna has the best S-parameter at 2.2 GHz and shows the expected behavior in the range of 2060-2230 MHz.

Now that the S-parameter is consistent, we will compare the radiation diagrams. According to the results we obtained from the CST program we analyzed, the main lobe direction in the radiation diagram of our antenna at 2145 MHz is 5º. HPBW was calculated as 70º.

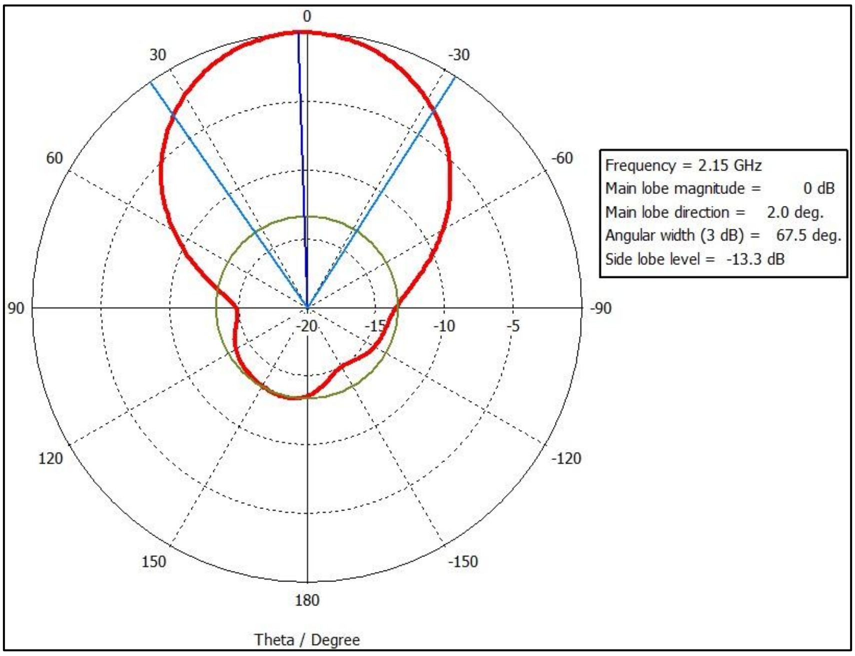


Figure 5.13. The measurement radiation pattern

Figure 5.13. shows the radiation pattern measurement result of the antenna. The radiation pattern was measured in the chamber located in METU-EE using an anechoic chamber. As seen in the figure, the main lobe direction parameter of the antenna at 2.15 GHz frequency has shifted by 2º. It was measured as 2º. In the analysis we made in CST, this value was 5º. Since the difference between them is reasonable, these two values are consistent. The HPBW value was also measured as 67.5º in the measurement. The same value was calculated as 70º in CST. Again, the difference between them is consistent. Since the analysis and measurement results have been consistent, we can conclude that the antenna design was done correctly.

Since no measurement result could be obtained from the axial ratio, this value could not be compared to simulation and measurement. However, based on the similarity in the S-parameter and the radiation pattern, we can comment that the axial ratio value will also be close.

At the beginning of this thesis, we designed an antenna that works at the S-band frequency value that we targeted. For a good circular polarization, we expect the axial ratio to be below 3 dB. In the thesis, we have shown that we have met the axial ratio value that we targeted with simulation. The target value for the S-parameter was to be below -10 dB in the desired frequency range. When we look at the graphs in the simulation results and measurement results, we see that we have met this requirement.

6. CONCLUSION AND RECOMMENDATIONS

The geometry of a circularly polarized cross-dipole satellite telemetry antenna is examined in this thesis. The design of the antenna was carried out using the antenna design software called CST, and the results are shared in this study.

In this study, a literature review was first conducted using articles related to similar topics. Subsequently, an antenna was designed in the CST program according to the determined fixed parameters. A series of analyses were carried out to understand the structure of the designed antenna, and these analyses are included in this study. Subsequently, these analyses were evaluated, and the main geometry was established and analyzed. There are three main parameters that we modified in the design of the antenna. These are the length of the dipoles, the angle of the dipoles, and the distance between the dipoles and the reflector. When looking at the results in Analysis-1, it was observed that the angle of the dipoles affects the antenna's S-parameter. Subsequently, the second analysis was conducted at the most optimized angle, and the reflector distance was varied. The results showed that as the reflector moved farther away, there was a deterioration in the S-parameter, and the final position of the reflector was determined. When the initial length of the dipoles did not achieve the desired radiation in the target frequency range, the final modification involved adjusting the lengths of the dipoles. Angle and reflector distance are fixed on the following analysis.

As seen in the analyses included in this study, a structure at the desired frequency value could not be achieved by changing only one parameter. Multiple parameters had to be modified to obtain the desired radiation and axial ratio values. Therefore, an optimized design is made. In this analysis where our variable parameters are dipole length, reflector distance and dipole angle, we realized that we could not obtain the desired values with only one parameter and then we made a design by changing all the values. As a result, we increased the length of the dipoles by 0.1 times. We gave the dipoles an angle of 20.11º and determined the distance of the reflector to the dipoles as 65.5 mm. When we made the analyses in this way, we saw that the axial ratio value of the antenna was 3 dB below in the desired range. In addition, our antenna had an S-parameter of -10 dB below in the same range. When we looked at the radiation pattern later, we saw that the HPBW value was 70º in the 65°-75º range that we targeted. Thus, we reached the values we targeted in CST.

After CST analysis, we made the antenna using copper materials and connected it to the network analyzer. When we connected it, we saw that the S-parameter value was the same as the analysis. Then we measured the radiation pattern and saw that the HPBW value was 67.5º. These values we obtained gave a consistent result with the analysis we made in CST. Thus, we have proven with the measurement results that we have made an antenna that meets the values we targeted at the beginning of the thesis.

When we search the literature, we can see many cross-dipole antennas that serve different purposes. In this study, we made a design to be used as a telemetry antenna in the air station. Since the determined telemetry frequency range of this aircraft is 2060-2230 MHz, we made a study to provide this range. As a future study, an antenna that will radiate with these optimized values in other band ranges can be designed to further develop this thesis. For example, we can make an antenna that will work in X-band. Or, we can keep the antenna in the S-band change the reflector geometry, and go for a different design that will show the effect of this geometry on radiation and axial ratio.

In addition, throughout all the analyses, we have always completed our analyses by increasing the lengths of the dipoles or by making them angle downwards towards the reflector. As another future work, we can shorten the dipole lengths or make the dipole angles angle upwards towards the reflector and go to new designs.

As another work, we can make another antenna design by reducing all the lengths of the antenna by a certain amount.

Since cross-dipole antennas continue to be used in many areas, future work studies that will develop this thesis can be further detailed and add antennas with different geometries to the literature.

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Gazili olmak ayrıcalıktır