

**T.R.
ONDOKUZ MAYIS UNIVERSITY
INSTITUTE OF GRADUATE STUDIES
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**



**FREQUENCY RECONFIGURABLE MICROSTRIP ANTENNA
SYSTEM FOR SATELLITE COMMUNICATIONS**

Ph.D. Thesis

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**SAMSUN
2024**

ACCEPTANCE AND APPROVAL OF THE THESIS

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ÖZET

UYDU İLETİŞİMLERİ İÇİN FREKANS YENİDEN YAPILANDIRILABİLİR MİKROŞERİT ANTEN SİSTEMİ

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Son yıllarda frekansı yeniden yapılandırılabilen antenler, uydu iletişimde önemli roller oynamaktadır. Bu antenler uydu iletişimde artan parazit, spektral yoğunluk ve sinyal girişimi problemleri için kritik çözümler sunmaktadır. Frekans kanallarında dinamik ayarlamalara olanak tanırken, kompakt yapılarıyla da çoklu anten sistemlerine alternatif işlevsellikler sağlamaktadır. Bu tezde frekans atlama yöntemi gerçekleştirilen, yenilikçi, frekansı yeniden yapılandırılabilir iki ayrı anten tasarımı sunulmaktadır.

Birinci anten tasarımı, S/C/X bantlarında çalışan, 16 yeniden yapılandırma modu ve 14 rezonans frekansını destekleyen bir mikroşerit antendir. Frekans ve ışıma örüntüsünde dinamik ayarlamalar yapabilen antenin verimliliğinin artması için benzetim tabanlı bir parametre tarama yöntemiyle parametrik optimizasyon gerçekleştirilmiştir. Bu yöntemle, besleme ile anten yapısı arasındaki eş-düzlem boşluk mesafesi optimize edilmiştir. CST ve HFSS araçları ile desteklenen gradyan tabanlı optimizasyon yöntemi kullanılmış ve benzetim sonuçlarına göre tasarım parametreleri değiştirilerek rezonans frekansı, verimlilik, ve genel performansının optimize edilmesi sağlanmıştır. $28.4 \times 30 \times 0.508 \text{ mm}^3$ boyutlarındaki anten, Rogers RT/duroid 5880 malzemesi ile dizayn edilmiş ve ADS ile optimize edilmiş bir kontrol devresiyle entegre edilmiştir. Hızlı anahtarlama dört RF PIN diyotu ile çalışan mikroşerit anten, bir modda %98 verimlilik sağlamıştır. Farklı bir modda da 6.34 dBi kazanç sunarak üstün performans göstermiştir.

İkinci anten tasarımı, D/THz bantlarında çalışan 6G uydu sistemleri için kompakt bir MIMO anten tasarımıdır. $2.951 \times 2.951 \times 0.127 \text{ mm}^3$ boyutlarındaki anten, altı frekans bandı arasında geçiş yapabilen dört PIN diyot ile entegre edilmiştir. Maksimum 8.27 dBi kazanç, %92 verimlilik ve -45 dB port izolasyonu sunan bu tasarım, modern uydu iletişim sistemleri için yeni performans standartları sunmaktadır.

Frekans atlama yönetimini kullanarak S/C/X bantlarında çalışan birinci ve D/THz bantlarında çalışan ikinci tasarım, anten teknolojisine yenilikçi katkılar sağlamaktadır. Bu tasarımlar gelecekteki kablosuz iletişim sistemleri içinde önemli bir referans niteliğindedir.

Anahtar Sözcükler: Frekans yeniden yapılandırılabilir anten, Mikroşerit anten, Uydu iletişimi, RF anahtarlama.

ABSTRACT

FREQUENCY RECONFIGURABLE MICROSTRIP ANTENNA SYSTEM FOR SATELLITE COMMUNICATIONS

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In recent years, frequency reconfigurable antennas have played a significant role in satellite communications. These antennas provide critical solutions to problems such as interference, spectral congestion, and signal jamming in satellite communications. By enabling dynamic adjustments in frequency channels and offering compact structures, they present functional alternatives to multi antenna systems. This thesis introduces two innovative frequency reconfigurable antenna designs that implement the frequency hopping technique.

The first antenna design is a microstrip antenna operating in the S/C/X bands, supporting 16 reconfiguration modes and 14 resonance frequencies. To enhance the efficiency of the antenna, which enables dynamic adjustments in frequency and radiation pattern, parametric optimization was performed using a simulation based parameter sweep method. Through this approach, the coplanar gap distance between the feed line and the antenna structure was optimized. Gradient based optimization supported by CST and HFSS tools was employed, and design parameters were modified based on simulation results to optimize resonance frequency, efficiency, and overall performance. The antenna, with dimensions of $28.4 \times 30 \times 0.508 \text{ mm}^3$, was designed using Rogers RT/duroid 5880 material and integrated with a control circuit optimized through ADS. The microstrip antenna, operating with four fast switching RF PIN diodes, and achieved 98% efficiency in one mode and demonstrated superior performance with a gain of 6.34 dBi in another mode.

The second antenna design is a compact MIMO antenna designed for 6G satellite systems operating in the D/THz bands. This antenna, with dimensions of $2.951 \times 2.951 \times 0.127 \text{ mm}^3$, was integrated with four PIN diodes enabling transitions between six frequency bands. This design delivers a maximum gain of 8.27 dBi, 92% efficiency, and -45 dB port isolation, setting new performance standards for modern satellite communication systems.

By employing frequency hopping management, the first design operating in the S/C/X bands and the second design operating in the D/THz bands contribute innovative advancements to antenna technology. These designs serve as significant references for future wireless communication systems.

Keywords: Frequency reconfigurable antenna, Microstrip antenna, Satellite communications, RF switching.

ACKNOWLEDGEMENT

I am profoundly grateful to the Department of Electrical and Electronics Engineering at Cairo University for their constant support during my doctoral studies. The department's commitment to academic excellence and innovation provided me with an enriching environment to conduct my research. I am especially grateful to my supervisor, Prof. Dr. Çetin KURNAZ, for his exceptional guidance, wisdom, and encouragement, which have been instrumental in the successful completion of this thesis. His mentorship has been a source of inspiration, and his dedication to both my academic and personal development is something I will always cherish. Additionally, I would like to extend my heartfelt thanks to my family, whose unwavering love, patience, and support have sustained me throughout this challenging yet rewarding journey. Their belief in me has been a constant source of strength, and without them, this accomplishment would not have been possible. To the esteemed faculty members of the department, thank you for your insights and for fostering a collaborative and intellectually stimulating atmosphere that has contributed to my growth. Without the support of both the department and my family, this work would not have been possible.

Fawzy A.F. ALSHARIF

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SYMBOLS AND ABBREVIATIONS

3D	: Three Dimensional
BSS	: Broadcast Satellite Service
CCs	: Correlation Coefficients
CPW	: Co Planar Waveguide
DARS	: Digital Audio Radio Service
DC	: Direct current
DGS	: Defected Ground Structure
EBG	: Electromagnetic Band Gap
ECC	: Envelope Correlation Coefficient
eMBB	: Enabling Enhanced Mobile Broadband
EMI	: Electro Magnetic Interference
FET	: Effect Transistors
FNBW	: First Null Beam Width
FR-4	: Flame Retardant-4
FSS	: Fixed Satellite Service
HFSS	: High Frequency Structure Simulator
HPBW	: Half Power Beam Width
INSAT	: Indian National Satellite
ISL	: Inter Satellite Links
ITU	: International Telecommunication Union
LMDS	: Local Multichannel Distribution Service
LTE	: Long Term Evolution
MEMS	: Micro Electro Mechanical System
MIMO	: Multiple Input Multiple Output
OWE	: Opportunistic Wireless Encryption
PBG	: Photonic Band Gap
PCB	: Printed Circuit Board
PIN	: Positive Intrinsic Negative
RF	: Radio frequency
SIMO	: Single Input Multiple Output
SMA	: Sub Miniature Version A
SRR	: Split Ring Resonator
UHF	: Ultra High Frequency
URLLC	: Ultra Reliable Low Latency Communication
UWB	: Ultra Wide Band
VHF	: Very High Frequency
VSWR	: Voltage Standing Wave Ratio
Wi-Fi	: Wireless Fidelity
WiMax	: Worldwide Interoperability for Microwave Access
WLAN	: Wireless Local Area Network

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1. INTRODUCTION

Antennas have long been considered a cornerstone of wireless communications, serving as a critical component in the transmission and reception of electromagnetic waves. Whether in terrestrial communications or satellite systems, antennas are fundamental to connecting distant points without the need for physical wires. Wireless communications Opportunistic Wireless Encryption (OWE) much of their existence to the pioneering work of early researchers like Galileo Marconi, who in the early 20th century made significant advances in signal transmission. His ground breaking work demonstrated the possibility of sending signals across vast distances, such as the Atlantic Ocean, despite the limitations imposed by the large dipole antennas of the time (Ghaffar et al., 2021). This marked the beginning of a new area in communication technology, as researchers began to explore ways to enhance the performance and functionality of antennas. As a result, the evolution of antenna design has progressed in parallel with the ever growing demand for faster, more reliable, and more versatile wireless communication systems. The swift advancement of wireless technology has led to numerous applications that demand various antenna types for effective operation. Each application, whether for communication, navigation, or surveillance radar. This necessitates designing antennas that are customized to fulfill specific operational requirements, including frequency range, polarization, and radiation pattern (Hussain et al., 2022). In many cases, different communication systems operate in distinct frequency bands or require unique polarization characteristics, which necessitates the use of specialized antennas. For example, the antennas used in military radar systems are often quite different from those used in commercial communications or navigation systems. This need for diversity in antenna characteristics has traditionally led to the installation of multiple antennas on a single platform. Nevertheless, incorporating numerous antennas into a single device or platform is often impractical, as it leads to an increase in the system's size, weight, and expense.

Moreover, maintaining multiple antennas also becomes logistically complex and financially burdensome. Given the limitations of deploying multiple antennas, there has been a growing trend toward integrating multiple functionalities into a single system. This need for integration is particularly evident in the field of modern communication devices, where space, cost, and efficiency are critical considerations.

As wireless applications continue to expand and evolve, it is no longer sufficient to dedicate individual antennas to each function. As an alternative, engineers and researchers are turning their attention to designing antennas that can fulfil multiple functions while reducing the system's size, weight, and complexity. One approach that has garnered significant interest is the creation of reconfigurable antennas. These antennas can modify characteristics like frequency, radiation pattern, and polarization to adapt to shifting operational demands. Their versatility makes them a highly appealing choice for applications where space and budget limitations are critical.

Reconfigurable antennas have become a promising innovation in wireless communications, thanks to their capability to adjust to varying operational conditions. They offer a practical solution to the problem of combining several wireless communication systems into one device. By dynamically changing their operating frequency, reconfigurable antennas can take the place of several traditional antennas, thereby reducing the overall footprint of the device (Jayanth et al., 2023). This capability is especially valuable in hand-held devices, where the inclusion of multiple antennas would not only increase the weight of the device but also take up more space. With the rise of smart phones, tablets, and other portable electronics, The demand for antennas capable of supporting multiple communication protocols is steadily increasing without adding unnecessary bulk to the device. Frequency reconfigurable antennas meet this need by offering a compact and efficient solution that can adapt to different frequency bands as required.

In many modern communication systems, frequency reconfigurable antennas are seen as an ideal solution for integrating multiple wireless communication systems into a single platform. Typically, each communication system would use its own dedicated antenna, but as devices become smaller and more complex, this approach becomes increasingly impractical. Hand-held devices, in particular, pose a unique challenge when it comes to antenna integration. Since hand-held devices are designed to be lightweight and portable, adding multiple antennas would increase the weight and occupy valuable space inside the device (Kumar et al., 2021). Reconfigurable antennas, by contrast, offer a way to consolidate these functions into a single, adaptable system that can switch between different frequency bands or operational modes as needed. This ability to reconfigure dynamically not only reduces the size and cost of the device but also improves overall performance by

allowing for more efficient use of available resources. Recent advances in microstrip antenna technology have further contributed to the growing interest in reconfigurable antennas. Microstrip antennas, which comprise a conductive patch situated above a grounded substrate, are known for their low profile, ease of fabrication, and ability to support multi-band operation (Karthika et al., 2023). In particular, frequency reconfigurable antennas can be integrated with the concept of frequency hopping, a technique that enhances security and resilience in communication systems. Frequency hopping involves rapidly switching the transmission frequency across a range of predetermined bands, making it more difficult for adversaries to jam or intercept signals. This ability to switch between frequencies not only helps mitigate jamming threats but also improves the robustness of the system in dynamic environments where interference is a concern. As the demand for more versatile and efficient communication networks continues to grow, the development of frequency reconfigurable antennas is emerging as a crucial aspect in shaping the future of wireless communications. These antennas provide a compact, cost-effective solution to the challenges posed by modern communication systems, especially in satellite communications, where constraints on space, weight, and power are critical. By adapting to different frequency bands and operational modes, including supporting frequency hopping for anti-jamming protection, reconfigurable antennas have the potential to become a cornerstone technology for the next generation of wireless communication devices.

In satellite communication systems, antennas operating in the regular S, C, and X bands are essential for various applications, such as data transmission, earth observation, and military communication. These bands are widely used due to their robust propagation characteristics and high data-handling capacity. However, the growing demand for bandwidth and the presence of interference in these regular bands necessitate the development of frequency reconfigurable antennas that can dynamically adapt to ensure optimal performance under varying conditions.

Simultaneously, the advent of 6G communication systems introduces the need for antennas capable of operating in higher frequency bands, such as the D-band. These frequencies promise ultra-high-speed data rates, low latency, and massive connectivity, which are critical for emerging applications like Internet of Things (IoT), autonomous systems, and next-generation satellite networks. Designing antennas for 6G satellite systems presents challenges, including achieving

compactness, maintaining efficiency, and ensuring high isolation in MIMO configurations. Combining the design of reconfigurable antennas for both regular bands (S, C, and X) and advanced 6G bands in one thesis addresses the pressing need to develop holistic solutions for diverse and evolving communication demands. By exploring these two critical domains within a single framework, this work not only bridges the gap between current and future communication technologies but also lays a foundation for seamless integration of systems that cater to both traditional and emerging applications. This approach provides a unified perspective on advancing frequency reconfigurable antenna technology for a broad spectrum of use cases, from legacy systems to next-generation networks, ensuring a comprehensive impact on the future of wireless communications.

1.1. Contributions of the Thesis

This dissertation presents significant advancements in the field of satellite communication through the design and development of two distinct antenna systems. These contributions address key challenges such as signal jamming and frequency reconfiguration, and offer innovative strategies for upcoming satellite communication technologies. A primary contributions are as follows:

- **Design and Implementation of a Frequency Reconfigurable Antenna for Satellite Communication:** First antenna design introduces a fully controlled frequency reconfigurable system able to function across an extensive frequency range (S, C, and X bands). This design provides a solution to the jamming issue by enabling 16 modes of frequency reconfiguration and achieving 14 resonance frequencies (3.27 GHz to 9.93 GHz). The system modifies both the frequency and radiation patterns to confuse potential jammers, ensuring secure and reliable satellite communication.
- **Development of a Quad-Port Multiple Input Multiple Output (MIMO) Antenna for Sixth Generation (6G) Satellite Communication:** The second antenna design is an innovative quad-port MIMO model tailored for operation within the 6G satellite frequency bands. This design incorporates frequency reconfiguration through a single PIN diode, offering two distinct operational modes that shift the resonance frequencies between 125 GHz and 198 GHz. Additionally, the high isolation between MIMO ports (-40 dB) and near-zero coherence coefficients

make this antenna highly effective for 6G satellite communication, contributing to the future of high-frequency satellite systems.

- Mitigation of Jamming through Frequency and Radiation Pattern Reconfiguration: Both antenna designs are strategically engineered to mitigate satellite jamming by altering frequencies and, in some cases, radiation patterns. This capability ensures secure data transmission even in scenarios where multiple high-power signals are transmitted over the same network. The directional radiation patterns and reconfigurable modes introduce a layer of protection against signal interference.
- Use of Advanced Materials and Simulation for Enhanced Performance: The designs utilize advanced materials, such as Rogers RT5880, for their substrates, which enhances efficiency due to low tangent loss. The use of CST Studio, ADS, Altium design and ANSYS HFSS software for modelling and simulation allowed for accurate optimization of the antenna performance, which was validated through fabrication results. The simulated and fabricated designs exhibit superior bandwidth expansion, gain, and efficiency compared to previous studies, demonstrating the practical viability of these designs for satellite communication systems.
- Advancement in Satellite Communication Technology for 6G and Beyond: By addressing the unique challenges of 6G satellite communication, such as high-frequency operation, bandwidth, and MIMO performance, this thesis contributes to the advancement of satellite technologies for future communication networks.
- Electrical Control Unit for Switches and Switching Analysis of the PIN Diodes: A significant challenge in the design and fabrication of the frequency reconfigurable antenna involved the electrical control unit (ECU) used for switching the PIN diodes. These diodes play a crucial role in reconfiguring the antenna's operating frequency by altering the impedance at specific points on the antenna structure. The switching mechanism must be precise and reliable to ensure that the antenna can operate correctly across the multiple frequency bands without degradation in performance.
- Interference and Crosstalk during Fabrication: While not as complex as MIMO antenna designs, the frequency reconfigurable antenna still required careful attention to the potential for interference between different components of the

antenna, particularly when modifying the frequency through switching mechanisms. Any undesired coupling between elements, especially during frequency reconfiguration, could impact the antenna's performance and its ability to maintain high efficiency and directivity.

These contributions collectively advance the cutting-edge advancements in satellite antenna design, providing innovative solutions to critical challenges such as jamming, frequency reconfiguration, and high-efficiency communication in satellite systems.

1.2. Thesis Content

This thesis is organized into five chapters. Chapter 1 serves as an introduction, delineating the primary problem addressed by this research and articulating the challenges that the proposed methodology aims to overcome. Chapter 2 provides a comprehensive review of foundational concepts essential to this study, including antenna design principles, key parameters, and evaluation metrics. It also presents pertinent information regarding satellite communications, establishing the theoretical framework for the proposed approach, while critically examining related studies in the field to analyse methodologies employed in prior research and synthesize their findings. Chapter 3 outlines the materials and methods utilized in this research, detailing the formulation and execution of analyses, feature extraction processes, modelling, simulation, and fabrication techniques employed for antenna classification. Chapter 4 presents the results of the newly developed antenna designs tailored for satellite communication systems, capable of operating across both conventional and 6G frequency bands, offering an in-depth discussion of the findings and their implications for the field. Finally, Chapter 5 wraps up the dissertation by highlighting the main research outcomes and proposing paths for future research to advance the development of the proposed methodology.

2. GENERAL INFORMATION

2.1. Introduction to Antenna

An antenna is a device that collects electromagnetic waves in free space and radiates the collected electromagnetic waves together with the transmission line (receiving antenna) or sends the signal from this transmission line as electromagnetic waves into free space (transmitting antenna) (Balanis, 2016). Figure 2.1 shows the antenna as a transmission device. As shown here, it serves as a transitional structure between free space and the antenna. The transmission line can be coaxial or a hollow tube (wave-guide). The transmission line is utilized to transfer electromagnetic energy from the source to the antenna and vice versa. There is a transmitting antenna when used to carry from the source to the antenna and a receiving antenna when used to carry from the antenna to the source.

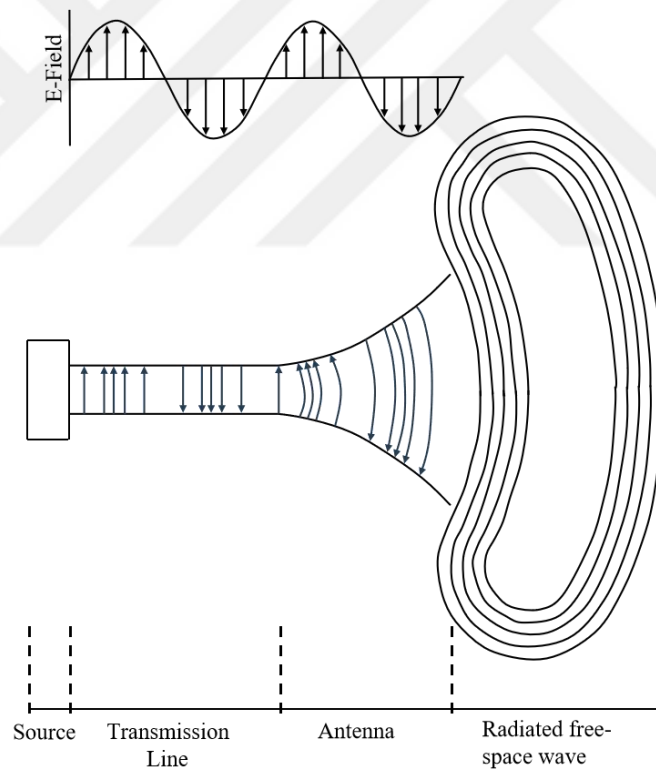


Figure 2.1. Antenna as a switching device (Balanis, 2016)

The Thevenin equivalent circuit of the transmission line illustrated in Figure 2.1 is shown in Figure 2.2. In this representation, the antenna connected to the transmission line is characterized by the load impedance, as described in Equation 2.1. The transmission line possesses a specific characteristic impedance, while the

source is modelled as an ideal generator. The antenna structure is associated with conduction and dielectric losses, represented by the load resistance, and the radiation emitted by the antenna is captured through the radiation resistance. The imaginary component of the antenna's impedance, related to radiation, is denoted (Omkumar, 2018).

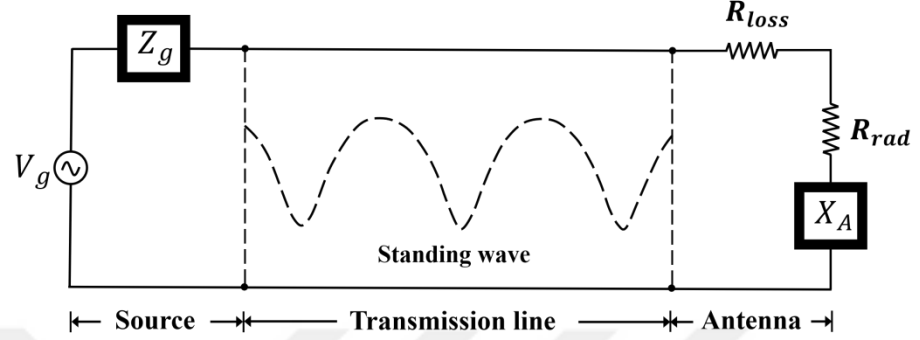


Figure 2.2. The equivalent circuit of a transmission line (Omkumar, 2018)

Ideally, the energy produced from the source shall transfer efficiently to the radiation resistance, which accounts for the antenna's radiation. However, in practice, various losses occur, including those from the transmission line, dielectric materials, and reflections at the junction between the transmission and the antenna. Reflected waves at this interface interact with waves travelling from the source to the antenna, resulting in standing waves along the transmission line. These standing waves create areas of concentrated energy storage, leading to patterns of constructive and destructive interference (Omkumar, 2018).

$$Z_A = (R_L + R_r) + jX_A \quad (2.1)$$

Where, Z_A represents the antenna load connected to the transmission line, which is the overall impedance presented by the antenna. The parameter R_L denotes the load resistance, a component of Z_A that accounts for the resistive losses in the antenna. R_r is the radiation resistance, which describes the part of the antenna's resistance that is responsible for radiating energy into space. Lastly, X_A denotes the imaginary component of the impedance related to antenna radiation, representing the reactive component, which arises from the energy retained in the antenna's near field. Antennas used in advanced wireless network devices are necessary to receive and transmit electromagnetic energy as well as to optimize or accentuate the radiant energy in the system in specific directions. Therefore, antennas must serve not only as a probing tool but also as a steering tool. To fulfil this requirement, they can take

various forms; pieces of conductive wire, apertures, patches, groups of elements (arrays), reflectors, lenses, etc (Omkumar, 2018).

2.2. Parameters of Antenna

Antenna effectiveness can be characterized through different factors, each reflecting different aspects of its functionality. While there are interrelationships among these parameters, not all need to be defined to fully assess an antenna's performance. The below section will outline the definitions of these key parameters.

2.2.1. Radiation Pattern

The antenna radiation pattern visually delineates how an antenna disperses energy relative to spatial coordinates. Established at the far-field area, this radiation pattern is contingent on directional coordinates and encompasses a variety of characteristics, including radiation intensity, power density, electric field strength, phase, polarization, and directivity. The electric or magnetic field detected at a constant distance is known as the amplitude field pattern, while the spatial distribution of power density at that same distance is designated as the amplitude power pattern. The field pattern, when represented on a linear scale, reflects the magnitude of the electric or magnetic field. In contrast, the linear scale power pattern illustrates the square of this magnitude, while the power pattern expressed in decibels (dB) represents the magnitude on a logarithmic scale.

Figure 2.3 provides a visual representation of a two-dimensional field pattern, along with both the power pattern on a linear scale and the logarithmic dB scale power pattern of a linear isotropic source antenna array, spaced at $d = 0.25\lambda$. In these representations, the minus and plus signs accompanying the lobes signify the relative amplitude polarization across the lobes as one traverses the gaps. To identify the points where the power pattern reaches half its maximum value referred to as the -3 dB points, we analyse the field pattern at 0.707 of its peak value, as illustrated in Figure 2.3(a), the linear scale power pattern at 0.5 of its maximum in Figure 2.3(b), , and the dB power pattern at -3 dB from its peak in Figure 2.3(c). In all three cases, the angular distance between the directions where the power falls to half of its peak is defined as the Half Power Beam Width (HPBW) or -3 dB aperture. The model depicted in Figure 2.3 consistently shows an angular separation of 64° between two points of half-power across all representations.

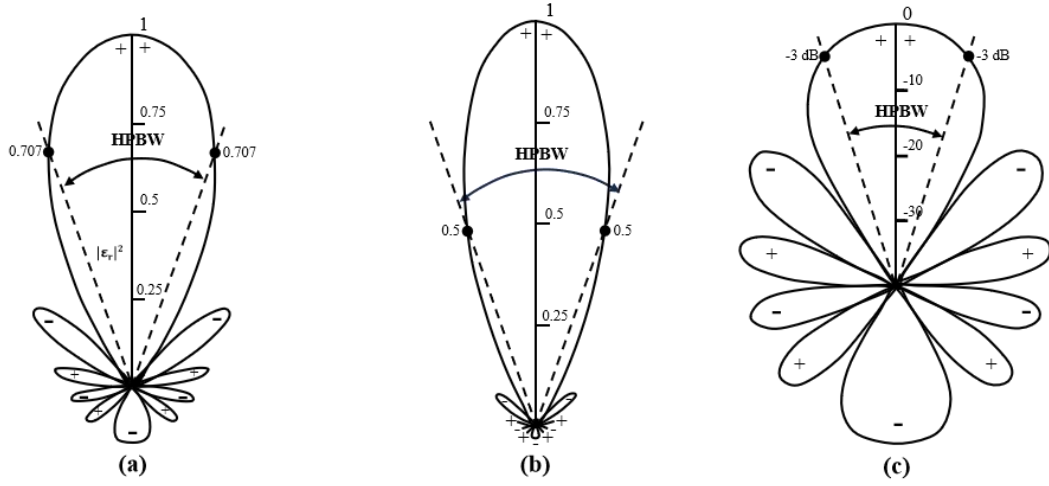


Figure 2.3. a) Field distribution (linear scale), b) Power distribution (linear scale), c) Power distribution (dB scale) (Bhattacharyya, 2024)

The components of a radiation pattern are known as lobes, which can be categorized into various types: the main lobe, minor lobe, side lobe, and back lobe. A radiation lobe represents a segment of the overall radiation pattern, delineated by areas of comparatively low radiation intensity. Figure 2.4(a) depicts a symmetrical two-dimensional polarized pattern showcasing multiple radiation lobes. Although some lobes may exhibit higher radiation intensity than other lobes, they are all collectively categorized as lobes, as depicted in Figure 2.4(b) (Bhattacharyya, 2024).

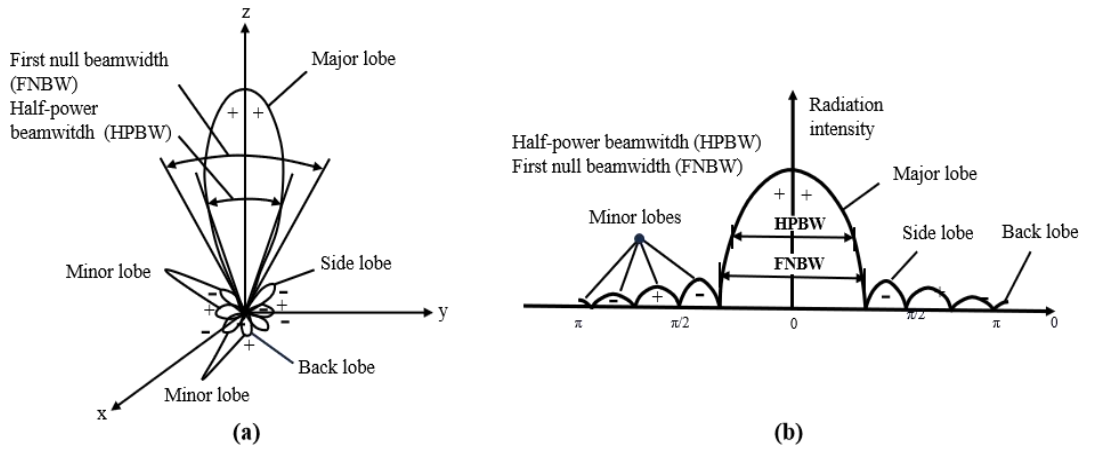


Figure 2.4. a) Lobes of the radiation pattern, b) Linear representation of the power pattern (Bhattacharyya, 2024)

The main lobe of an antenna is known as the radiation lobe that emits the highest amount of energy, typically oriented at an angle of $\theta = 0$, as illustrated in Figure 2.4. Some antennas may exhibit multiple main lobes, while any lobe that does

not qualify as the main lobe is categorized as a minor lobe. In Figures 2.4, all lobes apart from the primary one are categorized as minor lobes. A side lobe is specifically any radiation lobe that deviates from the primary intended direction, while a back lobe is positioned approximately 180° opposite the main lobe, usually representing a smaller lobe that radiates in the reverse direction relative to the main beam. Minor lobes are typically indicative of undesirable radiation and shall be reduced, with side lobes being the largest among these minor lobes. The side lobe level is quantified as the ratio of the power density of a side lobe to that of the main lobe, commonly referred to as the side lobe ratio or side lobe level. Generally, side lobe levels of -20 dB or lower are deemed unacceptable in most applications. Another important factor is beam width, which determines the angular range through which the antenna emits power. There are two main types of beam width: the half power beam width and the First Null Beam Width (FNBW). HPBW denotes the angular distance at which the radiation pattern's magnitude drops to 50% (or -3 dB) of the main beam's peak value.

This metric essentially identifies the region where power radiation is optimized, commonly termed peak power. The half-power beam width describes the angle at which the effective radiated power exceeds 50% of the peak value. This can be illustrated by drawing lines from the origin of the radiation pattern to the half-power points on the main lobe; the angle formed between these lines is referred to as the HPBW. Further clarification of this concept can be found in Figure 2.4. The mathematical expression for determining the half power beam width is detailed in Equation 2.2.

$$\text{HPBW} = \frac{70\lambda}{D} \quad (2.2)$$

Where, λ is the signal wavelength, and D is the antenna diameter.

The angular width between the first pattern zeros adjacent to the main lobe is called the first zero beam width. It is the angular separation drawn between the zero points of the radiation pattern on the main lobe. Starting from the beginning of the radiation pattern, tangents are drawn on both sides tangent to the main beam and the angle between these two tangents is defined as the first null beam width. Figure 2.4 shows the half power beam width and the first null beam width, labelled in a radiation pattern with small and large lobes (Bhattacharyya, 2024). The mathematical expression for the half-power beam-width is given in Equation 2.3:

$$\text{FNBW} = 2\text{HPBW} - 2 \left(\frac{70\lambda}{D} \right) = \frac{140\lambda}{D} \quad (2.3)$$

Antenna radiation patterns can be categorized into several types, including isotropic, directional, and omnidirectional patterns, detailed as below:

- **Isotropic Pattern:** An isotropic radiator is a theoretical concept representing a lossless antenna that emits radiation uniformly in every direction. While it is an idealized model and cannot be physically constructed, it serves as a benchmark for comparing the directional properties of actual antennas. An illustration of an antenna exhibiting isotropic radiation patterns as shown in Figure 2.5. In both Figure 2.5(a) and Figure 2.5(b), the radiation is distributed equally across all angles.

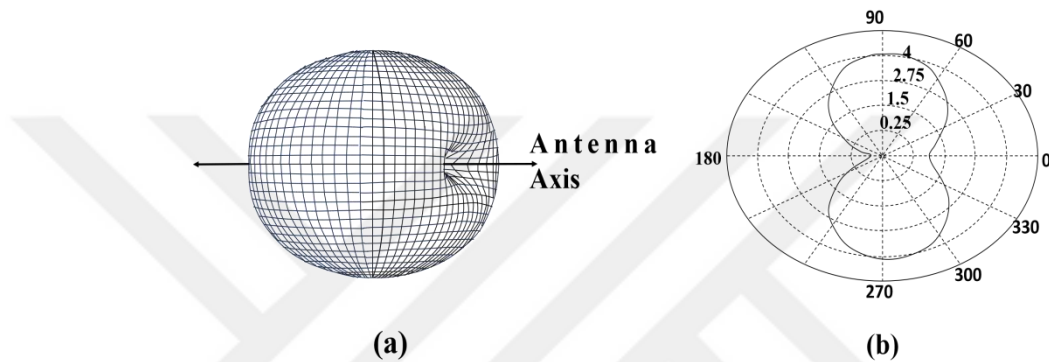


Figure 2.5. Isotropic radiation pattern: a) Three-dimensional representation, b) Two-dimensional representation (Bensky, 2019)

- **Directional Pattern:** A directional radiator refers to an antenna that emits or receives electromagnetic waves with greater efficiency in specific directions compared to others. This term typically applies to antennas that exhibit a maximum directivity significantly higher than that of a half-wave dipole. Figure 2.6 shows an example of an antenna that demonstrates directional radiation pattern in polar form.

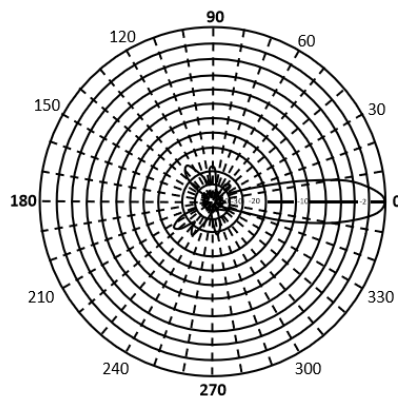


Figure 2.6. Polar form of directional radiation pattern (Bensky, 2019)

- **Omnidirectional Pattern:** The pattern design illustrated in Figure 2.7 is omnidirectional in the azimuth plane and directional in the elevation plane. This type of pattern is referred to as omnidirectional, defined by having an essentially omnidirectional pattern in one plane (specifically, the azimuth) and a directional pattern in any orthogonal plane (in this instance, elevation). Thus, an omnidirectional pattern represents a specific variety of directional pattern.

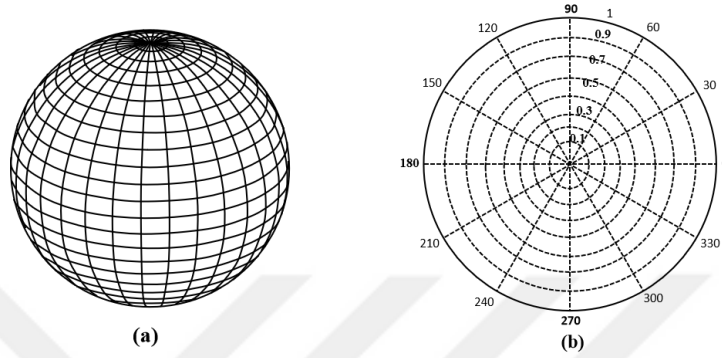


Figure 2.7. Omnidirectional radiation pattern, a) Three-dimensional representation, b) Two-dimensional representation (Bensky, 2019)

The areas surrounding an antenna can be classified into three distinct zones: the reactive near-field, the radiated near-field (Fresnel), and the far-field (Fraunhofer) zones. As illustrated in Figure 2.8, this classification helps to characterize the field structures within each region. While there are no sudden transitions in field configurations when moving between these zones, they exhibit clear differences. The boundaries that define these regions are not sharply delineated; however, various established criteria are commonly used to categorize them (Abdulhameed, 2021).

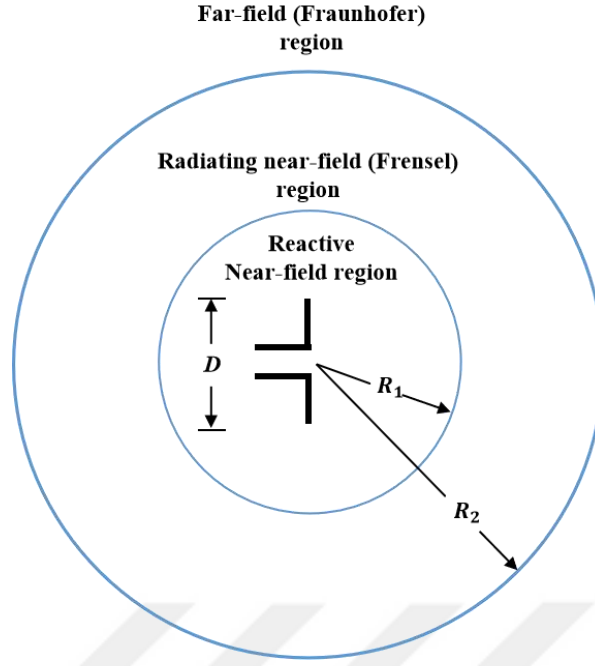


Figure 2.8. Field regions of an antenna radiation (Abdulhameed, 2021)

- **Reactive Near-Field Region:** The reactive near-field region refers to the part of the near-field area close to the antenna, where the reactive field is predominant. In many cases, this region's boundary is typically considered to coincide with the surface of the antenna, as described in Equation 2.4.

$$R_1 < \frac{0.62\sqrt{D^3}}{\lambda} \quad (2.4)$$

- **Radiating Near-Field (Fresnel) Region:** The radiating near-field region, often called the Fresnel zone, is the area located between the reactive near-field and the far-field regions of an antenna. In this zone, radiation fields dominate, and the angular distribution of the field changes with distance from the antenna, as shown in Figure 2.8. If the antenna's maximum dimensions are relatively small compared to the wavelength, the Fresnel zone can be considered minimal. On the other hand, if the antenna is significantly smaller than the wavelength, this zone might not exist at all. For most antennas, the approximate inner and outer limits of the Fresnel region are defined in Equation 2.5.

$$0.62\sqrt{\frac{D^3}{\lambda}} \leq R_2 \leq \frac{2D^2}{\lambda} \quad (2.5)$$

- **Far-Field (Fraunhofer) Region:** The far-field region, often referred to as the Fraunhofer zone, is characterized by an angular field distribution that remains largely unaffected by the distance from the antenna. This area is depicted in

Figure 2.8. Typically, the far-field region is recognized at distances beyond the limits specified in Equation 2.6. In this context, the inner boundary is defined by the radial distance outlined in Equation 2.6, while the outer boundary extends to infinity.

$$R > \frac{2D^2}{\lambda} \quad (2.6)$$

2.2.2. Directivity

Antenna directivity refers to the ratio of radiation intensity in a specific direction to the average intensity radiated in all directions. This concept is visualized in Figure 2.9. The average radiation intensity is determined by dividing the total radiated power by 4π . Simply put, the directivity of a non-isotropic source is the comparison of its radiation intensity in a given direction to that of an isotropic source. This relationship is mathematically represented in Equation 2.7 (Jonsson, 2012).

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \quad (2.7)$$

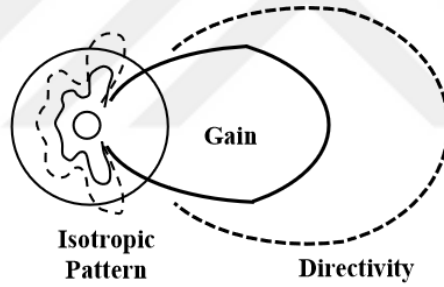


Figure 2.9. Antenna directivity and gain (Jonsson, 2012)

If direction is not specified, it means the direction of maximum radiation intensity (maximum directivity) expressed in Equation 2.8.

$$D_{max} = D_0 = \frac{U|_{max}}{U_0} = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}} \quad (2.8)$$

In this context, D represents the dimensionless antenna directivity, while D_0 is the maximum possible directivity. The radiation intensity is denoted by U , and U_{max} stands for the peak radiation intensity measured in watts per unit solid angle. U_0 refers to the radiation intensity of an isotropic source, and P_{rad} is the total radiated power (in watts). For an isotropic source, as indicated by Equations 2.7 and 2.8, the directivity equals unity since U , U_{max} , and U_0 are identical. Directivity quantifies how concentrated the antenna's radiation pattern is in a specific direction and is typically

measured in decibels (dB). A higher directivity implies a more focused beam, allowing the signal to travel further.

$$\text{Antenna Gain} = \text{Directivity} \times \text{Antenna Efficiency} \quad (2.9)$$

Gain refers to the combination of an antenna's efficiency and its directivity, as outlined in Equation 2.9. It's worth noting that greater directivity doesn't always offer benefits. For example, mobile devices usually use omnidirectional antennas, which emit signals uniformly across all directions and therefore exhibit lower directivity. On the other hand, antennas with higher directivity are commonly used in fixed set-ups, such as satellite communication and long-range wireless connections, where focusing the signal in a specific direction over long distances is crucial.

2.2.3. Antenna Efficiency

The efficiency of an antenna is defined as the ratio of the power input to the antenna to the power it radiates. An antenna with high efficiency effectively radiates a significant portion of the input power, while a low-efficiency antenna tends to absorb much of this power, resulting in losses either within the antenna itself or due to impedance mismatches that cause reflections. The reference terminals for antennas are shown in Figure 2.10.

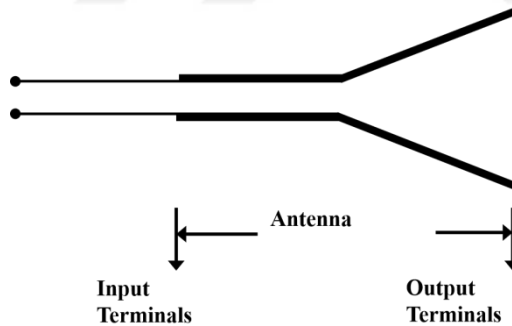


Figure 2.10. Antenna reference terminals (Balanis, 2016)

An antenna's efficiency remains constant regardless of whether it is transmitting or receiving signals. Thus, antenna efficiency can be described as the proportion of potential power that is received over all possible directions. More specifically, radiation efficiency, a type of antenna efficiency, is defined as the ratio of the power emitted by the antenna to the power supplied to it, as shown in Equation 2.10.

$$\epsilon_R = \frac{P_{\text{rad}}}{P_{\text{in}}} \quad (2.10)$$

Where, ϵ_R is the radiation efficiency of the antenna, P_{rad} is the radiated power by the antenna, and P_{in} is the input power applied. Equation 2.10 represents the radiation efficiency of an antenna, distinct from its total efficiency. Total efficiency is determined by combining radiation efficiency with losses resulting from impedance mismatch when the antenna is connected to a transmission line or receiver. This is expressed in Equation 2.11, where total efficiency encompasses both radiation efficiency and the losses attributed to impedance mismatches. Therefore, total efficiency factors in both the performance of the antenna and any power losses from mismatched impedance.

$$\epsilon_T = M_L \times \epsilon_R \quad (2.11)$$

Where ϵ_T is the total efficiency of the antenna, M_L is the material efficiency of the antenna, and ϵ_R is the radiation efficiency of the antenna. The total efficiency of an antenna is typically lower than its radiation efficiency. When there are no losses from impedance mismatch, the radiation efficiency aligns with the total antenna efficiency. Antennas rarely achieve 100% efficiency (0 dB) due to various factors, including conduction losses resulting from the finite conductivity of the metal used in the antenna, dielectric losses from the materials surrounding the antenna, and impedance mismatch losses.

2.2.4. Gain

Antenna gain is a crucial indicator of its overall performance. While it is closely related to directivity, gain also takes into account the antenna's efficiency. Directivity, by itself, measures how well the antenna concentrates energy in a specific direction, as shown by its radiation pattern. Gain, on the other hand, is defined as the ratio of the power radiated in a particular direction to the intensity that would be produced if the antenna radiated equally in all directions. The isotropic radiation intensity is derived from the input power supplied to the antenna, adjusted by an appropriate factor. This relationship is mathematically represented in Equation 2.12.

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

Where, G is the antenna gain, U is the radiation intensity, θ is the direction angle (radians), and ϕ is the radiation elevation angle (radians). Relative gain is typically defined as "the ratio of the power gain in a specified direction to the power

gain of a reference antenna in that same direction" (Balanis, 2016). This metric allows for the comparison of antenna performance, ensuring that the power input remains consistent for both antennas being evaluated. Commonly, the reference antenna may be a dipole, horn, or another antenna with a well-established gain. However, it is often the case that the reference is considered a lossless isotropic radiator. The calculation for relative gain can be expressed in Equation 2.13 .

$$G = \frac{4\pi U(\theta, \phi)}{P_{in}} \quad (2.13)$$

When a specific direction is not indicated, the power gain is typically measured in the direction of maximum radiation. The relationship between the total radiated power P_{rad} and the total input power P_{in} can be expressed as shown in Equation 2.14. This equation establishes the connection between the power delivered to the antenna and the power it radiates.

$$P_{rad} = e_{cd} \times P_{in} \quad (2.14)$$

2.2.5. Bandwidth

The bandwidth of an antenna refers to the range of frequencies over which the antenna's performance meets predefined standards, shaped by several characteristics of the antenna. Essentially, it highlights the frequency range where the antenna operates efficiently. Bandwidth can be measured in two primary ways, one method calculates it as the ratio of the highest to the lowest frequency, while the other expresses it as the ratio of the system's bandwidth to its centre frequency, as illustrated in Equation 2.15.

$$\frac{BW}{f_c} = \frac{f_H - f_L}{f_c} = 2 \frac{f_H - f_L}{f_H + f_L} \quad (2.15)$$

In defining bandwidth, it is important to note that antenna performance is assessed based on specific standards. The upper frequency f_H and lower frequency f_L values are determined by the condition where the return loss is below -10 dB or the corresponding Standing Wave Ratio (SWR) is less than 2. This threshold indicates the acceptable performance range of the antenna. The acceptable performance region may extend across a broad frequency range or be confined to specific segments, resulting in an antenna that supports multiple bands. The antenna presented in this thesis is designed as a dual-band antenna. An example of bandwidth as shown in Figure 2.11.

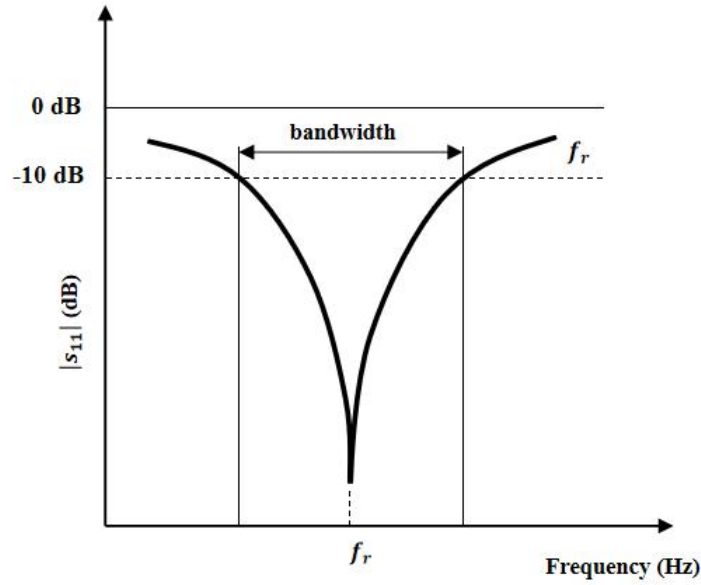


Figure 2.11. Bandwidth calculation example

2.2.6. Polarization

The polarization of an antenna in a given direction refers to the orientation of the electromagnetic wave it generates. If no specific direction is mentioned, the polarization is typically assumed to align with the direction of peak gain. In practical use, the polarization of the emitted energy can vary depending on the angle relative to the centre of the antenna, leading to different polarization properties across various sections of the radiation pattern. There are three primary types of polarization: linear, circular, and elliptical. If the electric field vector at a point remains consistently aligned along a straight line over time, it is considered linear polarization. In contrast, if the electric field describes an elliptical trajectory, the polarization is identified as elliptical (Wang et al., 2013).

- Linear polarization: The electric field can be composed of either a single component or two components, provided that there is no phase difference between them. When these two components are in phase, the resulting polarization is known as linear cross polarization. Additionally, there are two primary types of linear polarization: horizontal and vertical (Wang et al., 2013). In horizontal polarization, the electric field vector oscillates parallel to the ground, while in vertical polarization, it is aligned perpendicular to the ground. This difference is visually represented in Figure 2.12, with part (a) showing vertical polarization and part (b) illustrating horizontal polarization.

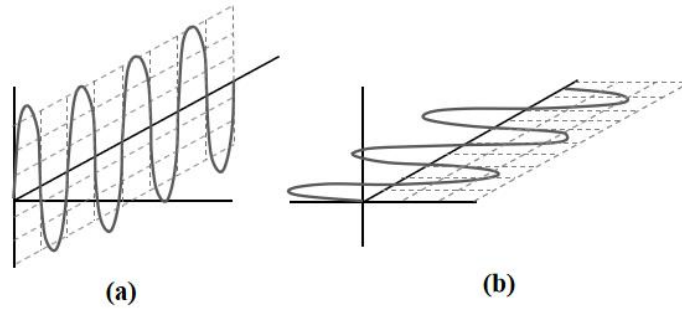


Figure 2.12. Linear polarization: a) Vertical polarization, b) Horizontal polarization

- Circular Polarization:** This type of polarization refers to a scenario where the electric field of an electromagnetic wave rotates at a constant speed while maintaining a consistent magnitude, always perpendicular to the direction of propagation. In this mode, the electric field vector spirals around the propagation axis as the wave moves forward. For an observer facing the wave, if the electric field vector rotates clockwise, the wave is described as right-hand circularly polarized. If it rotates counter-clockwise with a consistent amplitude, it is classified as left-hand circularly polarized. This occurs when two perpendicular electric field components have equal strengths and are 90 degrees out of phase, corresponding to a quarter-wavelength. The axial ratio is used to assess the relationship between the major and minor axes of the radiation pattern for a circularly polarized antenna. An ideal circularly polarized antenna has an axial ratio of 1 (or 0 dB). Circularly polarized antennas typically list axial ratios, with values closer to 0 dB indicating better performance. The distinction between right and left circular polarization, based on the rotation of the electric field vector, is depicted in Figure 2.13.

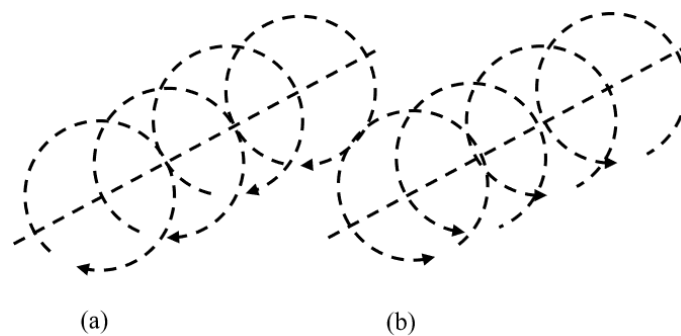


Figure 2.13. Circular polarization: a) Right-hand circular polarization, b) Left-hand circular polarization

- **Elliptical Polarization:** Electromagnetic waves with elliptical polarization consist of two electric field components, where the phase difference between these components remains consistently 90 degrees. This contrasts with linear polarization, which can also involve two components, but without the strict requirement of a 90-degree phase difference. In elliptical polarization, if the two electric field components have equal amplitudes, resulting in a 1:1 ratio, the polarization becomes circular. The Axial Ratio (AR) represents the ratio of the major axis to the minor axis in the radiation pattern of a circular polarized antenna. For elliptical polarization, the AR is always greater than 1 (>0 dB). When two plane waves differ in amplitude and are 90 degrees out of phase, elliptical polarization occurs, leading to an AR greater than 1. Figure 2.14 illustrates examples of elliptical polarization.

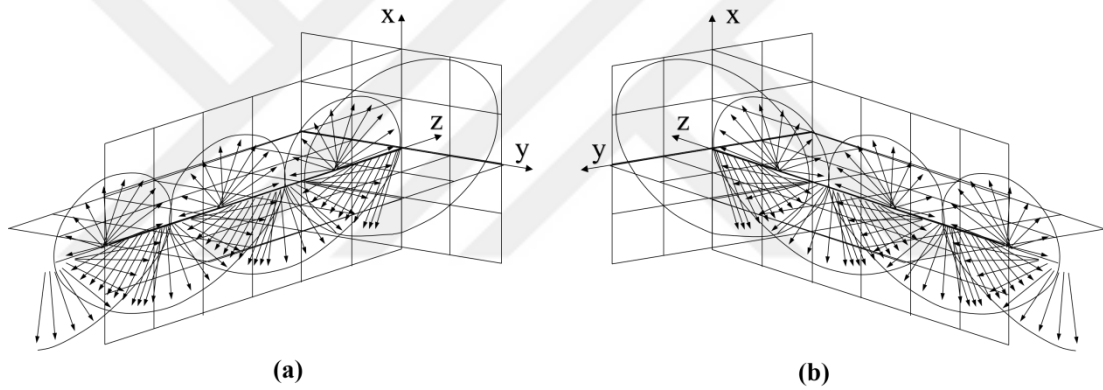


Figure 2.14. Elliptical polarization, a) Right hand elliptical, b) Left hand elliptical

2.2.7. Resonance Frequency

Resonance refers to the phenomenon where a system, typically a linear one, oscillates with greater amplitude at specific frequencies compared to others (Hirata et al., 2008). In electrical circuits, those containing both a capacitor and a coil are termed resonant circuits. In these circuits, the coil's magnetic energy is periodically converted into the capacitor's electrical energy, with the period of this conversion dictated by the values of the coil and capacitor. A series resonant circuit is formed when a coil and capacitor are connected in series, and the total impedance of this circuit can be determined using Equation 2.16.

$$Z_{\text{total}} = R_s + j(X_L - X_C) \quad (2.16)$$

Where, Z_{total} is the total impedance, R_s is the series resistance, X_L is the inductive reactance, and X_C is the capacitive reactance. For a frequency f_r ($X_L = X_C$), the reactive term is zero (Equation 2.17) and the total impedance of the circuit is purely resistive (real). This condition is called series resonance and the frequency f_0 is called series resonance frequency. The resonance frequency is calculated as in Equation 2.18.

$$X_L = X_C \quad (2.17)$$

$$f_0 = \frac{1}{2\pi fC} \quad (2.18)$$

2.2.8. Voltage Standing Wave Ratio

The Voltage Standing Wave Ratio (VSWR) represents the ratio between the peak voltage and the minimum voltage found in the standing wave pattern that forms along a transmission line. Its values range from 1 to positive infinity and are always positive. However, utilizing this definition can be complex without specialized instruments, such as a slotted line, especially given the varying interpretations of voltage in microwave structures. To simplify matters, VSWR is often referred to as Standing Wave Ratio (SWR), which emphasizes power waves instead of voltage. This perspective allows for a mathematical expression of VSWR in relation to the reflection coefficient. The reflection coefficient measures how much of an incident wave is reflected back by comparing the amplitude of the reflected wave to that of the incoming wave at a reference plane, with values ranging from -1 (indicative of a shorted load) to +1 (for an open load), and a value of 0 signifying a matched impedance load. This coefficient is a complex number, which aids in power measurements. The reflection coefficient, denoted as Γ , can be calculated based on the complex load impedance and the transmission line characteristic impedance can be complex. The formula for calculating the reflection coefficient is provided in Equation 2.19.

$$\Gamma = \frac{(Z_1 - Z_0)}{(Z_1 + Z_0)} \quad (2.19)$$

2.2.9. Return Loss

Return loss (RL) measures the amount of power reflected back to the antenna, indicating how much of the transmitted power is not absorbed by the antenna and is instead reflected. This dimensionless metric is often expressed in decibels (dB) to represent its values on a logarithmic scale. An antenna is deemed operable within a specific frequency range if its return loss is greater than -9.95 dB. Return loss, or scattering loss, serves as an effective means of characterizing S1:1 input and output sources. The return loss in dB can be calculated using Equations 2.20 and 2.21.

$$RL = -20 \log_{10} |\Gamma| \quad (2.20)$$

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_{in} - Z_s}{Z_{in} + Z_s} \quad (2.21)$$

Where, V_r is the amplitude of the reflected wave, V_i is the amplitude of the incident wave, Z_{in} is the input impedance, and Z_s is the characteristic impedance.

2.3. Types of Antennas

To get an idea of the types of antennas, some forms and definitions of the two types of antennas are used in this thesis.

2.3.1. Microstrip Antenna

Microstrip antennas, once primarily used for space applications, have evolved over time and are now widely utilized in various communication systems. These antennas can function within a frequency range of 100 MHz to 50 GHz. The design features a metal patch on a grounded substrate, and the patch itself can come in various shapes, though rectangular and circular designs are often preferred for their simplicity in analysis and production. Microstrip antennas offer numerous advantages, such as low production cost, thin structure, light weight, and compact size. They also allow for the integration of additional components like switches, mixers, and modulators onto the substrate. Despite their advantages, they have certain limitations, including narrow bandwidth, low gain, and limited power capacity. Figure 2.15 illustrates the microstrip patch antenna, which is commonly applied in fields like satellite networks, radar, military uses, wireless networks, scientific research, and medicine (Nguyen, 2016)

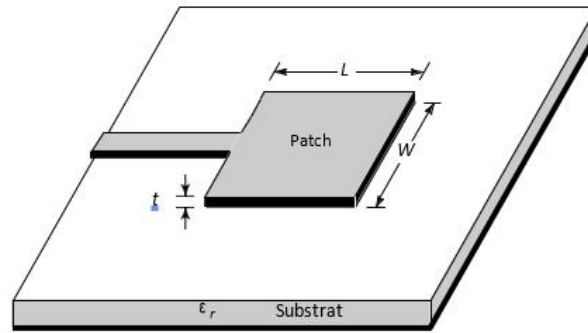


Figure 2.15. Microstrip patch antenna (Nguyen, 2016)

Where, W is the patch width, L is the patch length, and t is the patch thickness.

2.3.2. MIMO Microstrip Antenna

Multiple-Input Multiple-Output (MIMO) technology enhances communication performance by utilizing multiple antennas for simultaneous transmission and reception. This approach not only increases data rates by allowing multiple data streams to operate at the same frequency, but it also improves channel reliability through the use of various paths and reflections (Malviya et al., 2020). MIMO can be implemented in different configurations, including Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and full MIMO systems. The design of MIMO antennas is crucial for enhancing the efficiency of wireless communication systems (Malviya et al., 2020). Effective antenna design can yield benefits such as increased data rates, extended coverage areas, and more dependable connections. Moreover, MIMO antenna design is essential for advancing future wireless communication standards, including 5G and subsequent technologies. The MIMO antenna design process involves several stages, beginning with the identification of system requirements and culminating in prototype development and testing. When executed properly, MIMO antenna design significantly contributes to the creation of wireless communication systems that are faster, more reliable, and capable of broader coverage (Malviya et al., 2020).

2.4. Satellite Communications

A satellite communication is an artificial satellite allocated in Earth's orbit and equipped with transceiver equipment used for communication purposes. Communication satellites are utilized to transmit voice, data, video, and other communication signals between different points on Earth. They are commonly employed for communication services such as satellite phones, television broadcasts, and internet connectivity. Satellites are also used for purposes such as navigation, weather monitoring, and space exploration (Gagliardi, 2012).

The launching of satellites, once solely conducted by governmental agencies, has evolved into a progressively commercial endeavour (Maral, 2020). With the advancement of space industry and technology, private companies have ventured into satellite launching and achieved significant milestones in this domain. Increased competition and advancements in technology have reduced costs and made satellite launching services more accessible. For example, in 1960, an international telephone call cost \$1 per minute, but by the year 2000, this cost had dropped to below \$0.02 per minute (Gürsoy, 2021). According to the data from SIA in 2016, there were 1459 active satellites in orbit. When examined based on their purposes, a large portion of these satellites are dedicated to television services. Satellite-based television broadcasting plays a critical role in delivering programs to millions of viewers worldwide. Telecommunication services and internet services also have a significant share in satellite usage. The distribution of satellites in orbit based on application as shown in Figure 2.16 (Gürsoy, 2021).

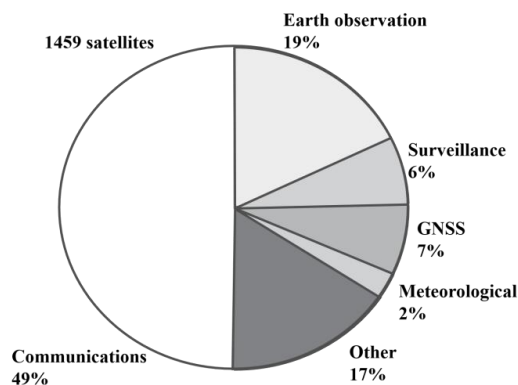


Figure 2.16. Distribution of satellites in orbit based on application (Gürsoy, 2021)

2.4.1. Ground to Ground

A ground-based station sends signals to the satellite, which collects these signals and forwards them to the designated ground station, enabling data communication. The system operates by utilizing carrier signals modulated in the form of electromagnetic fields. The satellite responsible for transferring the signal received from the ground-based station to another designated ground station is called a relay satellite, while the satellite responsible for configuring and transmitting the signal is termed a processing satellite. This facilitates the transmission of signals over longer distances (Gagliardi, 2012). Figure 2.17 shows the ground-to-ground satellite system.

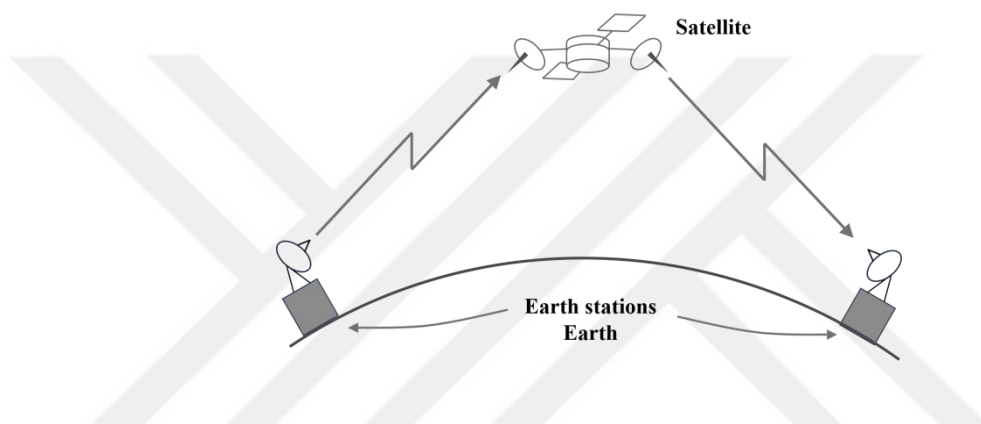


Figure 2.17. Ground to ground satellite systems (Gagliardi, 2012)

2.4.2. Ground Cross Link Ground

The ground-based station sends signals to the satellite; the satellite, in turn, relays the received signal to another satellite, which then transmits the signal to the designated target station, thereby enabling data communication. This system enables communication between distant ground stations that are not within the line of sight of the same satellite (Gagliardi, 2012). Figure 2.18 shows the ground cross-linked ground satellite system.

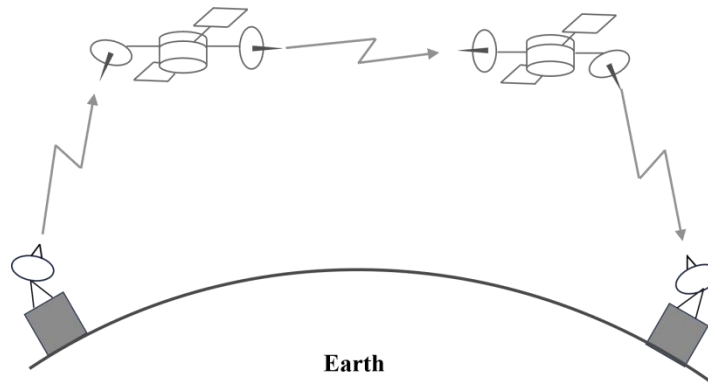


Figure 2.18. Ground cross link ground satellite systems (Gagliardi, 2012)

2.4.3. Ground to User Relay

This satellite relay system and ground stations include users near Earth, such as air-planes, drones, ships, etc. as well as satellites. Users can transmit data to ground stations via satellites (Gagliardi, 2012). Figure 2.19 shows satellite systems with ground-to-user transmission.

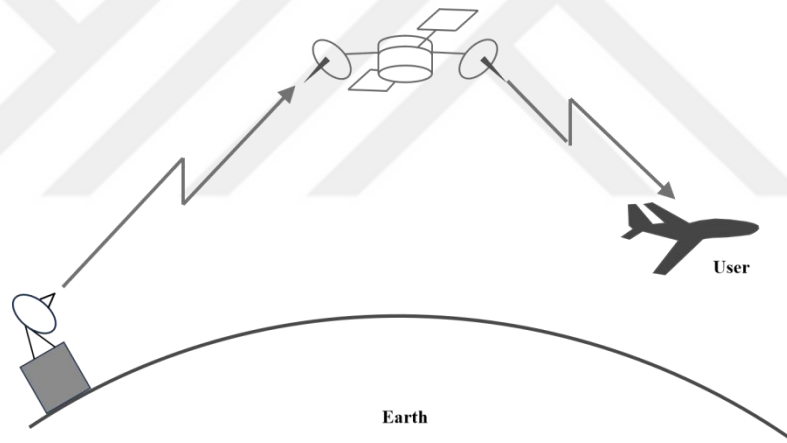


Figure 2.19. Ground to user relay satellite systems (Gagliardi, 2012)

2.5. Satellite Frequency Bands

In satellite communication, attention is paid to factors such as minimum spread distortion, power consumption, and noise in frequency selection (Gagliardi, 2012). The frequencies to be used for satellite communication are determined by International Telecommunication Union (ITU). ITU regulates the frequencies used for satellite communication and establishes international standards, ensuring that satellite communication is conducted worldwide in a coordinated manner. Frequencies under 100 MHz are affected by the ionosphere, either being refracted or reflected, which makes them unsuitable for satellite communication. Therefore,

frequencies above 100 MHz are preferred for satellite communication. The frequency bands used for this purpose include Very High Frequency (VHF), Ultra High Frequency (UHF), as well as L, S, C, X, Ku, and Ka bands. These bands are chosen based on the specific communication requirements and applications (Gagliardi, 2012). The operational frequency ranges for these bands are detailed in Table 2.1, and their characteristics are depicted in Figure 2.20.

Table 2.1. Satellite communication frequency bands

Band	Frequency Range (GHz)	Applications
L	1-2	Mobile Satellite Service, GPS
S	2-4	Mobile Satellite Service, Digital Audio Radio Service, deep space research
C	4-8	Fixed Satellite Service (FSS), Broadcast Satellite Service (BSS)
X	8-12.5	FSS military communication, remote sensing satellites
Ku	12.5-18	FSS, BSS
K	18-26.5	FSS, BSS, LMDS
Ka	26.5-40	FSS, LMDS, ISL (Inter Satellite Links), satellite imaging

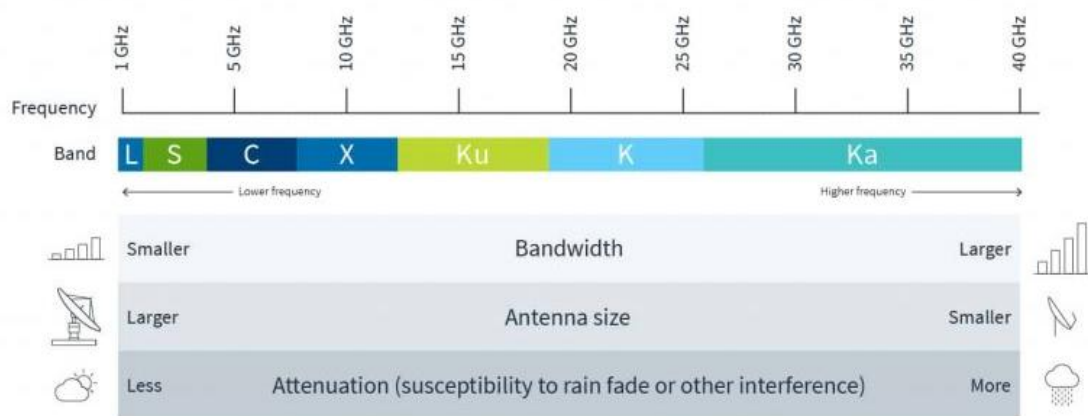


Figure 2.20. Satellite frequency bands (Gagliardi, 2012)

2.5.1. S-Band

S-Band is utilized in applications such as mobile satellite services, Digital Audio Radio Service (DARS), mobile satellite services, and deep space research. The S-Band operates within the frequency range of 2 GHz to 4 GHz and is commonly used in space communication. Its popularity in this field is largely attributed to its low background noise, making it an ideal choice for clear and reliable communication (Sheppard, 2004; Jama, 2002).

2.5.2. C-Band

The C-band, which operates within the 4 GHz to 8 GHz frequency range, is widely utilized in applications such as Fixed Satellite Services (FSS) and Broadcast Satellite Services (BSS). Its stability and ability to perform well under various weather conditions make it suitable for long-distance communication and reliable broadcasting. C-Band is often preferred due to its low sky noise power and low susceptibility to rain fade. The availability of equipment compatible with the C-Band frequency range is a positive factor, but there is also a disadvantage, such as the requirement for larger antenna sizes (Sheppard, 2004; Jama, 2002).

2.5.3. X-Band

X-band is a frequency band preferred for fixed applications by government and military users. The X-band operates within the frequency range of 8 GHz to 12 GHz. Its service quality is similar to C-Band. It is utilized for military communication, radar systems, and some commercial applications (Sheppard, 2004; Jama, 2002).

2.5.4. Sixth Generation Bands

6G technology is anticipated to utilize Terahertz (THz) frequency ranges, which are much higher than those currently employed in mobile communication systems. The Terahertz spectrum spans roughly from 300 GHz to 3 THz, sitting above both microwave and millimeter-wave frequencies (Wikströmet et al., 2020). This expanded frequency range promises enhanced data transmission rates and improved communication capabilities in future networks.

- 7 GHz to 20 GHz: This lowest frequency band being considered for 6G is currently in use for various 5G applications, offering an optimal balance between range and capacity (Wikströmet et al., 2020).
- W-band (75 to 110 GHz): This higher frequency band exceeds the 7 to 20 GHz range in terms of capacity but compromises on range, making it more suitable for fixed wireless applications rather than mobile use (Wikströmet et al., 2020).
- D-band (110 to 175 GHz): Operating at an even higher frequency than the W-band, this band provides greater capacity; however, its very limited range makes it appropriate only for fixed wireless applications and satellite communications (Wikströmet et al., 2020).
- Bands between 275 and 300 GHz: These ultra-high frequency bands offer exceptionally high capacity, but their restricted range limits their application to fixed wireless scenarios.
- THz range (0.3 to 10 THz): The extremely high frequency bands in this range provide unmatched capacity, yet their short range makes them suitable exclusively for fixed wireless applications (Wikströmet et al., 2020).

2.6. Satellite Jamming

Wireless networks are highly vulnerable to jamming attacks due to the open nature of their communication channels, making it easier for attackers to interfere with the transmission of signals by overwhelming the network with noise or malicious signals. Jamming devices can disrupt data transmission integrity between two legitimate wireless participants by continuously emitting Radio Frequency (RF) signals or by sending meaningless, regular data packets. These tactics aim to interfere with or disrupt communication on the network by obstructing or corrupting legitimate communication (Wenyuan et al., 2006). The difference between jamming and Radio Frequency Interference (RFI) lies in their intent. Jamming attacks are intentional, whereas RFI is an unintentional occurrence, typically resulting from nearby transmitters using the same or similar frequency ranges. In such cases, devices can interfere with each other, leading to unwanted signal distortions (Mpitiopoulos et al., 2009).

2.7. Jamming Attacks Methods

Jamming devices can employ various attack strategies to interfere with other wireless communications.

2.7.1. Constant Jamming Attacks

Constant jamming attacks are conducted by constantly transmitting high-power radio signals to prevent legitimate users from receiving data packets. This type of attack also blocks legitimate users access to the channel. Due to the constant transmission of high-power radio signals, energy consumption is high (Xu et al., 2005). Figure 2.21 shows the constant jammer Received Signal Strength Indicator (RSSI) output.

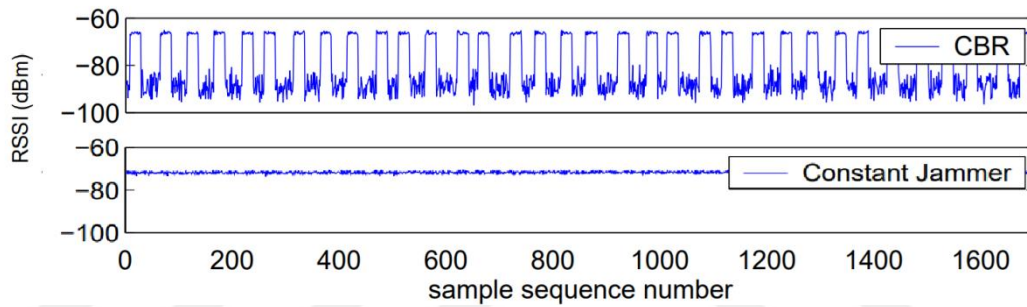


Figure 2.21. Change of signal strength received over time (Xu et al., 2005)

2.7.2. Deceptive Jamming Attacks

Deceptive jamming attacks interfere with the channel by constantly sending consecutive regular packets, rather than randomly sending bits at a specific frequency or across a broader frequency range. As a result, the receiving device may remain in receiving mode, believing that these regular packets are coming from a legitimate source. This allows the attacker to achieve their goal of causing harm to the network while concealing their presence (Xu et al., 2005). Figure 2.22 shows the deceptive jammer RSSI output, also its clear that the constant jammer and deceptive jammer have roughly the same average values, with the slight difference in the plot values.

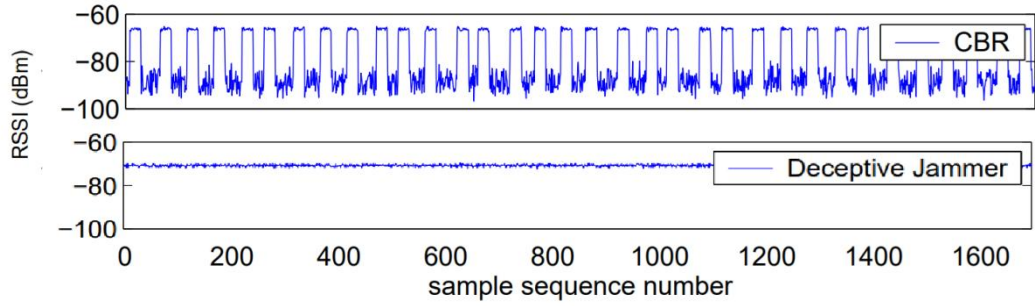


Figure 2.22. Change of signal strength received over time (Xu et al., 2005)

2.7.3. Random Jamming Attacks

Random jamming attacks are carried out not by constantly transmitting high-power radio signals, but by entering a sleep mode for a certain period after conducting an attack for a specific duration. This way, energy saving is achieved. The sleep and attack periods can be predetermined fixed duration or random duration (Xu et al., 2005). Figure 2.23 shows the random jammer RSSI output.

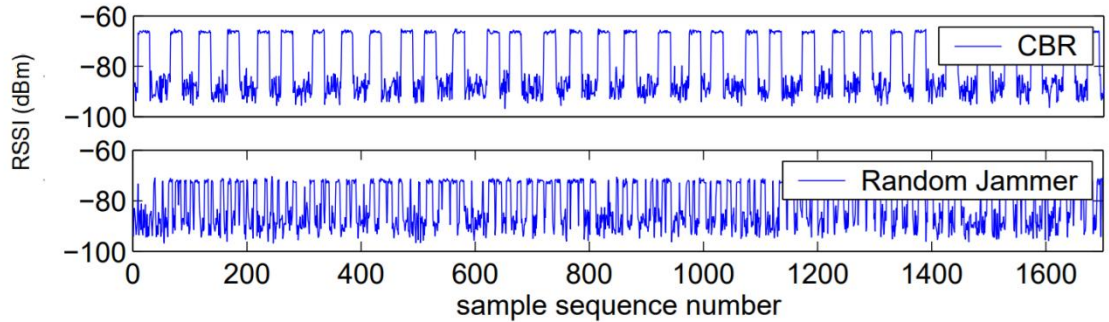


Figure 2.23. Change of signal strength received over time (Xu et al., 2005)

2.7.4. Reactive Jamming Attacks

The jammer remains in a listening mode when there is no data transmission on the channel. Once data transmission occurs on the channel, it emits radio signals. This type of attack is more sophisticated than constant jamming, as it conserves energy by jamming only when there are transmissions, occurs when the attacker detects legitimate packets being transmitted on the channel and subsequently intervenes. The average values of the constant jammer and deceptive jammer are roughly the same, the small differences in the graph are due to the experimental setup. The conceptual differences in the figures are crucial for understanding the technical

details and underlying mechanisms of the discussed topic. A detailed explanation could be added to better clarify these differences. Energy efficiency is high as it does not constantly attack jamming. Timing is crucial for a reactive jamming attack. Figure 2.24 shows the reactive jammer RSSI output (Xu et al., 2005).

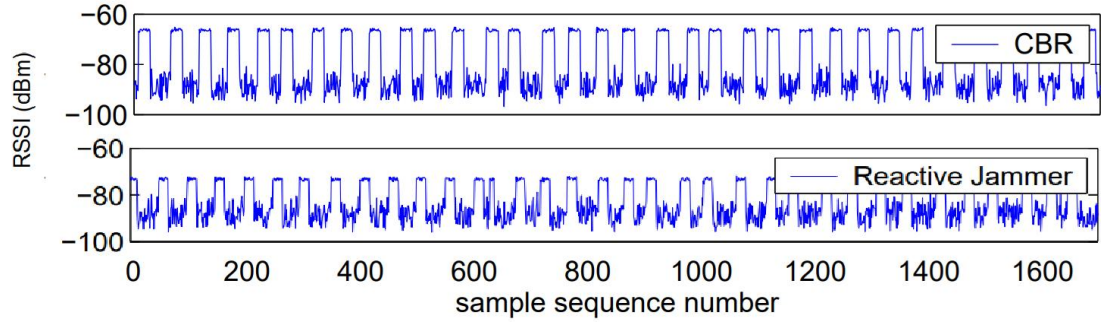


Figure 2.24. Change of signal strength received over time (Xu et al., 2005)

2.8. Anti-Jamming over Antenna Model

Anti-jamming solutions are systems used to prevent interference with communication and reduce noise. Recently started to use antennas have ability to reconfigure their properties to change the tranceiving ways between the transmitter and receiver simultaneously such as frequency, radiation pattern and polarization, that will construct confused in jamming side and solve the problem over same hardware components (Chaoet al., 2021).

2.8.1. Antenna Frequency Reconfiguration

Frequency reconfigurable antennas, by design can transition between multiple frequency bands. The resonance frequency of an antenna is determined by its physical structure and electrical length. To reconfigure the frequency of the antenna, it is necessary to change the antenna's physical length using electrical configuration techniques, alter the antenna's impedance, or modify its electrical characteristics (Gürsoy, 2021).

2.8.2. Antenna Pattern Reconfiguration

Reconfigurable antennas with adaptable radiation patterns are commonly developed by incorporating movable or rotatable structures, or by utilizing interchangeable parasitic elements that are reactively loaded. The reconfiguration of the radiation pattern is accomplished by modifying the current distribution across the antenna. One of the main challenges in this process is ensuring that the input

impedance remains consistent while adjusting the primary currents on the antenna. The most straightforward approach to implementing reconfiguration is by physically rotating the entire antenna structure using movable components (Gürsoy, 2021).

2.8.3. Antenna Polarization Reconfiguration

The polarization of an antenna is dictated by the direction of the electrical current. Reconfigurable antennas have the ability to switch between different polarization types while maintaining their frequency responses and radiation patterns. This ability to alter polarization is especially useful in portable devices, as it helps minimize polarization mismatch losses and improve communication efficiency (Khan et al., 2021).

2.8.4 Antenna Compound Reconfiguration

The compound reconfigurable method provides the flexibility to adjust multiple antenna parameters simultaneously. By employing this method, antenna designs can be created where several parameters, such as frequency, radiation pattern, and/or polarization, can be reconfigured. For instance, in a mobile communication system, efficiency can be enhanced by dynamically shifting the frequency band of an antenna to a less crowded spectrum region while simultaneously directing the radiation beam in the desired direction (Ojaroudi et al., 2020).

2.9. Antenna Frequency Reconfiguration Techniques

By adjusting parameters like the physical structure and electrical properties of the antenna, its performance can be reconfigured to meet specific requirements. These modifications allow for fine-tuning or optimizing the antenna's operation, adapting it to different conditions or applications. This flexibility in design is illustrated in Figure 2.25, various methods for ensuring reconfigurability can be categorized into four main categories (Ojaroudi et al., 2020).

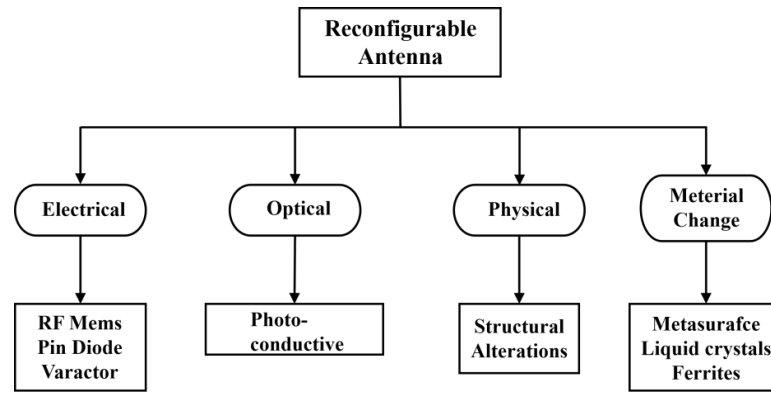


Figure 2.25. Techniques for enabling reconfigurability

2.9.1. Physical Reconfiguration Technique

Antennas physically modifying their structures. This technique involves altering the radiating elements of the antenna's design without employing any switching mechanisms. By adjusting the physical layout, the antenna's performance can be adapted to different operational needs (Ojaroudi et al., 2020).

2.9.2. Material Change Reconfiguration Technique

Reconfiguration occurs by exploiting changes in the dielectric constants or magnetic permeability of various materials such as liquid crystals, ferrite, dielectric fluids, under different conditions (Ojaroudi et al., 2020).

2.9.3. Optical Reconfiguration Technique

The fundamental principle in optical reconfiguration relies on exposing semiconductor materials to laser light of suitable wavelengths to increase the conductivity of the semiconductor material. This technique does not require external circuitry but necessitates laser light for activation (Ojaroudi et al., 2020).

2.9.4. Electrical Reconfiguration Technique

Electronic switching components play a crucial role in electrically reconfigurable antennas by modifying surface current distributions, This structural modification alters the antenna's radiation characteristics or radiation boundaries. Key components used to achieve this reconfiguration include Radio Frequency Microelectromechanical Systems (RF-MEMS), PIN diodes, varactor diodes, and Field Effect Transistors (FETs), which play essential roles in adjusting the antenna's performance and operational behaviour. effectively manage these components, an

integrated control circuit is essential for the adjustable antenna, allowing for transitions between designated operating frequencies. The advantages and disadvantages of various reconstruction techniques are summarized in Table 2.2 (Tan et al., 2013).

Table 2.2. Comparison of reconfiguration techniques

Techniques	Advantages	Disadvantages
Physical reconfiguration	No bias (no voltage drop)	Slow response Energy consumption Prototyping is difficult High cost
Material change reconfiguration	Lightweight and flexibility	High response time Limited commercial applicability High cost
Optical reconfiguration	No bias (no voltage drop)	Continuous power consumption Complex
Electrical reconfiguration	Low cost Implementation flexibility	Energy consumption

- **RF MEMS Switch:** MEMS switches achieve the transition between open and closed positions using electrostatic force. The primary advantage of MEMS switches compared to solid-state devices like FETs or PIN diodes is their significantly lower series resistance, which leads to reduced signal loss. Additionally, MEMS switches require less power to operate, making them more energy-efficient for reconfigurable antenna applications. The internal structure of the RF MEMS switch as shown in Figure 2.26 (Tan et al., 2013).

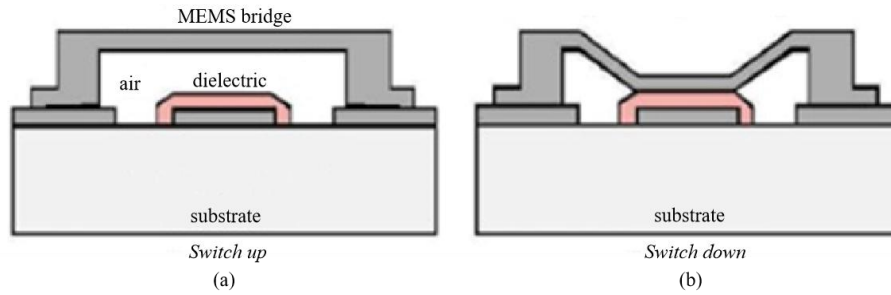


Figure 2.26. RF MEMS switch, a) Inactive case, b) Active case (Tan et al., 2013)

- Varactor diode: Diodes whose capacitance changes according to the applied voltage. They can be used for frequency tuning in RF applications (Tan et al., 2013).
- PIN diodes: PIN diodes are solid-state diodes used in the reconfiguration of antenna properties. A PIN diode is a semiconductor switching element that operates like a resistor that varies with voltage. In an ideal PIN diode, the desired condition is for the internal resistance to be zero when the switch is open and infinite when the PIN diode is closed. The equivalent circuits for the forward bias (a) and reverse bias (b) of the PIN diode as shown in Figure 2.27 (Tan et al., 2013).

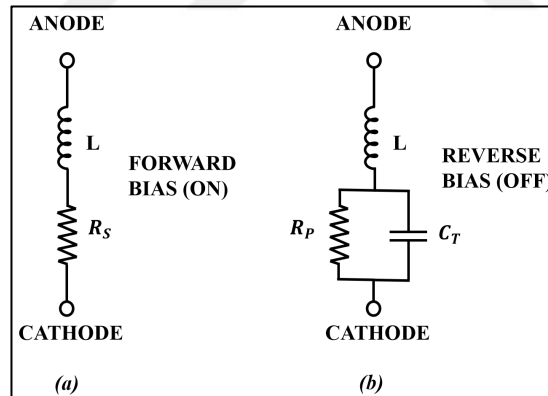


Figure 2.27. PIN diode equivalent circuit, a) Forward bias, b) Reverse bias (Tan et al., 2013)

Between the P-type and N-type layers, there exists a wide intrinsic (in-doped) region, often referred to as the depletion region. This intrinsic layer acts almost like a high-resistance barrier; that is, it contains very few charge carriers (electrons and holes). As a result, the passage of current is blocked when the diode is in the off state. However, when a forward voltage is applied across the diode, with the positive terminal connected to the P-type side and the negative terminal to the N-type side,

the depletion region narrow, it reduces the width of the depletion region. More charge carriers are added to the intrinsic layer, reducing its resistance. This allows the diode to become conductive, enabling current flow through the diode. The fast switching capability, reliability, low cost, wide operating frequency range, and compactness of the PIN diode make it a desirable choice for design implementation as shown in Table 2.3 (Tan et al., 2013).

Table 2.3. Comparison of various RF switches.

RF Switch	Advantages	Disadvantages
RF MEMS	Wide frequency range High isolation	High cost High control voltage Very complex Fluctuations in capacitance value
Varactor	High tuning precision Low control power requirement	Non-linear Voltage dependency High cost
PIN diodes	Very reliable High response time Easy to use Bias control unit Low cost	Voltage drop

2.10. Literature Review

This section presents a review of general studies related to frequency reconfigurable antennas, providing an overview of key research developments in the field.

2.10.1. Brief of Studies Related to Regular Satellite Applications

Numerous studies in the literature have explored the use of frequency reconfigurable antennas. A selection of these studies is outlined below for further discussion.

(Zhang et al., 2022) introduces study introduces a multi-frequency reconfigurable spherical helix antenna intended for satellite network applications. The antenna's reconfiguration is enabled by incorporating a Positive Intrinsic Negative (PIN) diode, with a structure measuring 80 mm in height and consisting of two wire segments separated by a switch. The antenna operates in two distinct frequency ranges: 2.25 GHz and 3 GHz when the diode is inactive, and 1.4 GHz, 2.0 GHz, and 2.5 GHz when the diode is active. In the active configuration, the measured bandwidths for the resonant frequencies are 100 MHz, 230 MHz, and 180 MHz, respectively. The antenna achieves a maximum gain of 4.23 dBi at 1.4 GHz. Despite these features, the design has limitations, such as relatively low gain, significant voltage drop during diode activation, noticeable size, and restricted bandwidth.

(Mabrouk et al., 2022) introduces a multi-frequency reconfigurable microstrip antenna specifically designed for C-band satellite communication applications. The antenna's ability to adapt to different frequency bands is achieved through the integration of four PIN diodes. With overall dimensions of 99.6 mm by 99.6 mm, the antenna consists of seven layers and features a switch placed every 42 degrees across the main patch. It demonstrates resonance in two frequency bands: 5.85 GHz and 6.56 GHz when the first diode is activated; 5.68 GHz and 6.49 GHz with the second diode; 5.48 GHz and 6.40 GHz with the third diode; and 5.21 GHz and 6.29 GHz with the fourth diode. Each resonant frequency provides a bandwidth of 200 to 250 MHz. However, the design faces challenges due to its considerable size and the complexities introduced by the multiple layers, which could result in increased fabrication difficulties and costs during implementation.

(Ghaffar et al., 2021) presents an antenna reconfigurable its frequency at 5G sub-6 and ranges of S-band satellite communication applications. The antenna utilizes a micro striping technique to achieve its reconfigurability. Measuring 40 mm by 50 mm, the structure comprises three layers and employs Rogers RT/6010 material as its substrate. It is engineered to resonate at two specific frequencies: 1.65 GHz and 2.51 GHz, and a maximum bandwidth of 150 MHz. The proposed antenna achieves a maximum gain of 2.2 dBi and an overall efficiency of 80%. Nonetheless, the design is limited by its relatively large dimensions and lower efficiency.

(Sreelakshmi et al., 2020) introduces an antenna reconfigurable its frequency that well-suited for wireless communication applications. The antenna's

reconfigurability is made possible through the use of two distinct PIN diodes. Featuring a compact design of $24 \times 19 \text{ mm}^2$, the antenna is composed of three layers and constructed with a flexible poly-amide substrate that is 1.53 mm thick. It can resonate at three distinct frequencies: 2.4 GHz, 1.65 GHz, and 2.51 GHz. The proposed antenna achieves a maximum bandwidth of 180 MHz, a peak gain of 3.14 dBi, and an overall efficiency of 83%. However, its design is constrained by relatively larger dimensions and moderate efficiency.

(Ghaffar et al., 2020) presents an antenna reconfigurable its frequency for multi-band wireless communication networks. The antenna's reconfigurability is enabled by two distinct PIN diodes. With dimensions of $26 \times 22 \text{ mm}^2$, it features a three-layer configuration utilizing Rogers TMMR-4 as the substrate. The antenna can resonate at two adjustable frequencies: 3.5 GHz and 6.78 GHz. It demonstrates a maximum bandwidth of 560 MHz, achieving a maximum gain of 3.1 dBi and an overall efficiency around 80%.

(Hussain et al., 2022) introduces an antenna reconfigurable its frequency for multi-band satellite communication applications. Its reconfigurability is accomplished through a single PIN diode. The antenna measures $35 \times 25 \text{ mm}^2$ and is built with two layers, using polytetrafluoroethylene as the substrate material. It operates at two adjustable frequencies, specifically 5.2 GHz and 5.8 GHz. The design offers a maximum bandwidth around 210 MHz, attaining a maximum gain of 4.2 dBi and an overall efficiency of 85%.

(Saraswat and Harish, 2019) introduces a dual-frequency, dual-polarization Co-Planar Waveguide (CPW)-fed monopole antenna, offering reconfigurability across specific frequency bands, making it suitable for satellite communications across multiple frequency ranges. The use of a single PIN diode allows for frequency reconfiguration. With dimensions of $50 \times 33 \text{ mm}^2$, the two layer antenna uses a transparent PETP film substrate. It operates at two different frequencies: 2.25 GHz and 3.25 GHz, and achieves a 195 MHz bandwidth, a maximum gain of 3.2 dBi, and an overall efficiency of 82%.

(Awan et al., 2021) presents a small-sized CPW-fed antenna with frequency reconfigurability, designed specifically for C-band satellite communications. It utilizes a single PIN diode for switching between frequencies, and has compact dimensions of $21 \times 15 \text{ mm}^2$. The antenna is able to resonate at 3.5 GHz and 4.5 GHz,

with a bandwidth of 220 MHz. The design achieves a peak gain of 2.2 dBi and an overall efficiency of 79%.

(Ullah et al., 2021) introduces a frequency switchable microstrip patch antenna designed primarily for mobile wireless applications. The antenna's frequency reconfigurability is enabled by the integration of two PIN diodes. Measuring $37 \times 35 \text{ mm}^2$, the design features three layers and utilizes FR-4 as the base material. The top layer consists of two co-planar patches that are strategically aligned without a ground plane and linked via an inset microstrip line. This antenna can operate across four frequency ranges, depending on the switching modes of the diodes. Specifically, Mode 1 resonates at 3.3 GHz, Mode 2 at 2.1 GHz, Mode 3 at 3.5 GHz, and Mode 4 at 2.45 GHz. The gain varies from 1.44 to 2.2 dBi, while the bandwidth extends between 200 MHz and 920 MHz. The antenna's radiation efficiency ranges from 80% to 91%.

(Rao et al., 2021) covers the design and evaluation of a frequency tunable microstrip patch antenna, targeting Ku and K-band satellite communications. The antenna's reconfigurable nature is facilitated by the use of two PIN diodes. Manufactured from FR-4 material, it has dimensions of $68.9 \times 89.4 \text{ mm}^2$ and resonates at two frequencies: 14.9 GHz and 25.5 GHz, with bandwidths of 800 MHz and 950 MHz, respectively. When the first diode is triggered, the antenna delivers a maximum gain of 3.35 dBi at 14.9 GHz; when the second diode is active, the resonance shifts to 25.5 GHz, producing a gain of 7.24 dBi and an efficiency of 0.78. However, the design faces challenges due to the low radiation efficiency of the substrate material, which limits its performance in broadcast satellite communications.

(Kumar et al., 2021) provides a comprehensive review of frequency reconfigurable microstrip antennas designed for 4G, 5G, and C-band satellite communication systems. The antenna's frequency agility is achieved by incorporating six PIN diodes. The antenna, with a three-layer structure, is built using FR-4 substrate and has dimensions of $35 \times 40 \text{ mm}^2$. It is designed to resonate at four different frequencies: 2.5 GHz for 4G, 5.8 GHz for 5G, and 6.8 GHz for C-band satellite communications. Each frequency provides a bandwidth of 200 to 400 MHz, while the gains recorded at these frequencies are 2.3 dBi, 3.5 dBi, and 3.6 dBi. However, the design faces some limitations, including its relatively large size,

restricted bandwidth, and the lower gain achieved at the designated resonance frequencies.

(Sharma et al., 2020) introduces a reconfigurable microstrip patch antenna intended for use across several frequency bands, including those compatible with Bluetooth, INSAT downlink frequencies, and X-band satellite communications. Constructed from FR-4 material, the antenna has compact dimensions of 22×28 mm². It is designed to resonate at three main frequencies: 2.45 GHz, 4.72 GHz, and 7.41 GHz, with corresponding bandwidths of 200 MHz, 600 MHz, and 300 MHz. The gains achieved for Bluetooth, INSAT, and X-band are 3.13 dBi, 4.25 dBi, and 4.08 dBi, respectively. Furthermore, the radiation efficiency for these bands is 81%, 82%, and 81%. Despite its capabilities, the design is hindered by relatively low gain, and the FR-4 substrate exhibits poor performance in satellite communication due to lower radiation efficiency.

(Singh and Lohar, 2020) outlines a frequency adjustable microstrip antenna, developed for use in radar-based satellite communication systems. The antenna utilizes PIN diodes for its reconfiguration capabilities and has a size of 30×36.7 mm². It operates at four different frequency bands: 9.42 GHz, 14.87 GHz, 17.74 GHz, and 20.79 GHz, depending on which diode is activated. The antenna offers bandwidths ranging between 200 MHz and 300 MHz, and achieves a peak gain of 4.24 dBi at 20.79 GHz. A notable feature of this design is its radiation pattern, which covers a broad area, providing uniform coverage across different signal planes.

(Mishra et al., 2020) explores a frequency switchable microstrip patch antenna designed for C-band and X-band satellite communication applications. The antenna achieves its frequency reconfiguration via two PIN diodes and is constructed using FR-4 material with dimensions of 27×8 mm². It operates across two frequency bands: 7.02–8.45 GHz, with a fractional bandwidth of 18.48%, and 10.83–11.71 GHz, with a bandwidth of 7.80%. The respective gain values for these frequency ranges are 2.04 dBi and 1.85 dBi, with an efficiency rating of 81.2%. Despite its versatility, the antenna's performance is constrained by limited bandwidth and lower gain in C-band frequencies.

(Singh et al., 2019) introduces a circularly polarized patch antenna with adjustable frequency that uses two PIN diodes and a Defected Ground Structure (DGS) to modify the behaviour of the ground plane. The design is optimized for multiple wireless systems, such as WLAN, WiMAX, and satellite communications in

the C-band. Built from FR-4 material, the antenna is compact with dimensions of $25 \times 25 \text{ mm}^2$. It operates at five different frequency points: 4.80 GHz, 5.32 GHz, 6.01 GHz, 6.22 GHz, and 6.41 GHz. The highest gain recorded is 3.85 dBi at 6.41 GHz, and the antenna offers a 250 MHz bandwidth when the first diode is inactive and the second diode is switched on.

(Sun et al., 2019) explores a multi-frequency rectangular patch antenna with reconfigurable capabilities, designed for L/S-band satellite communications. The reconfiguration is achieved using a single PIN diode. The antenna, made from an FR-4 substrate, has compact dimensions of $124 \times 124 \text{ mm}^2$. It functions at a single frequency of 1.65 GHz when the diode is off, and when the diode is activated, it operates at 2.2 GHz and 2.6 GHz. The bandwidths at these frequencies are 100 MHz, 80 MHz, and 150 MHz. The maximum gain recorded for this antenna is 3.2 dBi at 2.2 GHz, though the design is hampered by low gain, power loss when the diode is active, large physical size, and narrow bandwidth.

(Yin et al., 2019) introduces a reconfigurable microstrip antenna designed for satellite communications in the L and S bands. Two MEMS switches enable frequency tuning. The antenna, which measures $140 \times 70 \text{ mm}^2$, is constructed with three layers, with FR-4 material used as the substrate. It can operate at four specific frequencies: 1.485 GHz, 2.820 GHz, 0.817 GHz, and 0.760 GHz, depending on the activated switch. The bandwidths for these frequencies are 650 MHz, 523 MHz, 40 MHz, and 120 MHz, respectively. Gain values measured for these resonant frequencies are 2.5 dBi, 1.25 dBi, 3.2 dBi, and 2.88 dBi. However, the antenna's design is constrained by its large size, low gain, and limited bandwidth across its operational modes.

(Sayem et al., 2019) discusses a stacked microstrip antenna with frequency reconfigurability, specifically designed for L/S-band satellite communication. The ability to switch frequencies is made possible by the integration of two PIN diodes. The antenna, measuring $41 \times 60 \text{ mm}^2$, comprises three layers, each using RO4003 material as a substrate. When the first switch is engaged, the antenna operates at 1.55 GHz and 2.0 GHz. Activating the second switch shifts the frequencies to 1.85 GHz and 2.15 GHz. The corresponding bandwidths for these configurations are 300 MHz and 450 MHz, and the recorded gains are 7.5 dBi and 3.9 dBi. However, the design is constrained by its larger physical size and limited bandwidth for each frequency configuration.

(Zhu et al., 2015) presents a microstrip antenna capable of frequency reconfiguration, developed for C-band satellite communication. The antenna utilizes a meta-surface design to enable reconfiguration. With dimensions of $40 \times 45 \text{ mm}^2$, this three-layer antenna is constructed using FR-4 material. The antenna operates at 4.8 GHz and 5.3 GHz, with respective bandwidths of 800 MHz and 400 MHz. Gain values are measured at 3.5 dBi at 4.8 GHz and 5.5 dBi at 5.3 GHz. Although effective, the antenna's performance is somewhat hindered by its larger size and the passive reconfiguration method employed.

(Khan and Rahman, 2020) highlights a reconfigurable antenna design with G-shaped elements, allowing it to function at multiple frequencies ranging from 3 GHz to 10 GHz. The design leverages two PIN diodes to enable reconfigurability across different signal directions. The antenna, fabricated using FR4 material with a thickness of 1.6 mm, features dimensions of $40 \times 48 \text{ mm}^2$ and includes a partial ground plane. It is suitable for several applications, including WLAN, WiMAX, long-range radio communication, and X-band satellite systems. The antenna demonstrates a gain of 1.22 dBi with 85% efficiency at 3.5 GHz, a gain of 1.92 dBi with 84% efficiency at 5.25 GHz, and a gain of 2.11 dBi with 83% efficiency at 6.31 GHz. Moreover, the antenna achieves a 2.74 dBi gain and 79% efficiency when operating within the 5.94 to 9.07 GHz frequency range.

(Karthika and Kavitha, 2023) outlines a small, low-profile antenna with dimensions of $38 \times 40 \times 0.787 \text{ mm}^3$, designed to provide flexibility in tuning both frequency and radiation properties. The antenna is constructed using Rogers RT Duroid 5870 as the primary substrate material. Frequency tuning is accomplished using three PIN diodes, with each diode paired with sections of varying lengths that correspond to distinct resonance frequencies. By switching the diodes on and off, the antenna can operate across four unique frequency bands. The antenna offers gains of 2.24 dBi at 5.3 GHz, 2.38 dBi at 3.82 GHz, 3.72 dBi at 2.77 GHz, and 3.12 dBi at 2.2 GHz. The antenna employs the SMP1345-079LF PIN diode, and meticulous isolation between RF and DC signals is ensured. This design is particularly advantageous for 5G network applications.

(Ullah et al., 2022) introduces an antenna with frequency reconfigurability, capable of switching across three distinct frequency ranges through the use of four integrated PIN diodes, enabling various operational configurations. The antenna has dimensions of $30 \times 20 \times 1.6 \text{ mm}^3$ and is fabricated using FR-4 substrate, with a

thickness of 1.6 mm, making it well-suited for 5G, Wi-Fi, and X-band satellite communications. The gain measurements are 1.67 dBi at 2.45 GHz, 1.56 dBi at 3.1 GHz, 1.69 dBi at 3.8 GHz, 1.65 dBi at 4.1 GHz, 4.24 dBi at 7.8 GHz, and 3.49 dBi at 9.5 GHz.

(Parida, 2024) presents a dual-port antenna design created for Cognitive Radio (CR) applications. The antenna integrates a broadband monopole sensing element with a narrowband communication component. Constructed using an FR-4 substrate, it has dimensions of $40 \times 50 \times 1.6 \text{ mm}^3$. The performance measurements show gains of 2.27 dBi at 3.85 GHz, 4.7 dBi at 5.98 GHz, and 6.16 dBi at 10.02 GHz. This compact design provides an effective solution, making it particularly well-suited for C-band and cognitive radio systems.

(Dam et al., 2023) proposes a wearable T-shaped dual-band antenna that operates via a Co-Planar Waveguide (CPW) and is specifically designed for on-body wireless communication systems. The antenna is tuned to function at 2.4 GHz and 5.2 GHz. Fabricated with RT/Duroid 5880 material, the antenna's dimensions are $30 \times 34 \text{ mm}^2$ with a thickness of 0.8 mm. The gain values recorded for this design are 1.4 dBi at 2.4 GHz and 6.25 dBi at 5.2 GHz. This solution represents a promising advancement in wearable wireless communication technologies.

(Johnson et al., 2020) introduces a reconfigurable antenna utilizing adhesive polyimide tapes. The proposed design employs Rogers Arlon DiClad 880 as its substrate. Measurement results indicate successful performance at 2.4 GHz, resulting in a gain of 7 dBi. The antenna dimensions are $159 \times 152 \times 3.175 \text{ mm}^3$, making it suitable for CubeSat applications.

(Nan et al., 2021) presents a compact monopole antenna that offers eight distinct states of frequency reconfiguration, specifically engineered for Ultra Wide Band (UWB) applications to satisfy requirements for anti-interference and multifunctionality. Constructed on an F4B substrate, the antenna measures $22 \times 13 \times 0.8 \text{ mm}^3$. Incorporating the MA4AGBLP912 PIN diode from M/A-COM, this design operates within the frequency ranges of 3.19–4.58 GHz, 5.26–6.21 GHz, and 7.87–8.73 GHz, attaining a gain of 5 dBi along with an efficiency rate of 80%. This approach significantly enhances UWB performance while effectively mitigating interference from Wi-MAX, C-band, WLAN, and X-band signals.

(Qin et al., 2020) proposes an innovative frequency reconfigurable antenna based on a surface-integrated wave-guide, targeted at S-band and C-band

applications. The design, fabricated on a Rogers RT/duroid 5880 substrate, features dimensions of $53.5 \times 53.5 \times 1.575 \text{ mm}^3$. For reconfigurability, the antenna utilizes the SMP1345 SC-79 PIN diode. The measured operational frequency ranges include 2.406 GHz to 2.424 GHz and 5.683 GHz to 6.005 GHz, yielding gains of 1.26 dBi, 2.37 dBi, 6.26 dBi, and 6.74 dBi. The study reports radiation efficiencies ranging from 70% to 90% in high-frequency mode and 30% to 40% in low-frequency mode.

(Lakshmi et al., 2020) introduces a hybrid reconfigurable antenna characterized by an asymmetric ground structure, constructed on a polyimide substrate. The dimensions of the antenna are $43 \times 28 \times 0.2 \text{ mm}^3$, employing the bar 64 model PIN diode for switching operations. The antenna operates across several frequency bands: 2.3 GHz, 3.8 GHz, 4.5 GHz, 5.1 GHz, 6.3 GHz, and 6.8 GHz. The boasting a peak gain of 4 dBi, with an efficiency of 74%. This asymmetrical design is especially appropriate for applications in the S and C bands, including Long Term Evolution (LTE), Wi-Fi, WLAN, and fixed satellite services.

(Jun Li et al., 2020) discusses the development of a frequency adaptable antenna designed specifically for flexible devices and conformal surfaces. The antenna features a stub-loaded circular radiator constructed on an RTS5880 flexible substrate with a thickness of 0.254 mm. By employing stub loading and slot etching methods, the design provides multiple advantages, including a compact form factor, adjustable frequency capabilities, a wide impedance bandwidth, and consistent radiation patterns while maintaining comfortability. The integration of two PIN diodes enables this reconfigurability. Both simulations and experimental findings demonstrate that the antenna effectively operates across various commercial frequency bands, including the S-band (2 GHz–4 GHz), Wi-Fi frequencies at 3.6 GHz, 5.8 GHz, and 5.9 GHz, as well as 5G sub-6 GHz frequencies at 3.5 GHz and 4 GHz. The highest recorded gain is 5.31 dBi, with an efficiency of 87.3%.

(Prudhvinadh et al., 2019) presents a reconfigurable circular slotted antenna designed for WiMAX and X-band wireless communication applications. This compact antenna measures $32 \times 24 \text{ mm}^2$ and employs CPW feeding to optimize its performance, incorporating BAR-64-20V PIN diodes for tuning capabilities. The addition of an L-shaped resonator within the circular slot facilitates operation along the transmission line, allowing for dual-band functionality. The antenna effectively operates within the WiMAX frequency range (3.1–4.5 GHz) and the X-band (10.3–11.7 GHz), making it suitable for space research and mobile radio astronomy

applications. It exhibits a maximum efficiency of 90% and a gain of 3.6 dBi, demonstrating reliable performance across these frequency bands.

(Fertas et al., 2020) introduces a compact monopole antenna mounted on a semiconductor and fed through a CPW. With dimensions of $24 \times 29 \text{ mm}^2$, the antenna is intended for adjustable frequency applications across WiMAX, WLAN, LTE, and X-band satellite communication systems. Utilizing an innovative radiating patch element that incorporates slots and switches, the antenna achieves reconfigurability. Simulations and measurements conducted on an FR-4 substrate confirm the antenna's functionality across several frequency bands, specifically 2.37–2.75 GHz, 3.15–4.08 GHz, 4.48–5.92 GHz, and 6.69–8.31 GHz. The study provides a comprehensive evaluation of the antenna's reflection coefficient, current distribution, and radiation characteristics, with empirical results closely aligning with simulation data. The maximum gain achieved by the antenna is 4.58 dBi.

(Singh and Sharma, 2021) introduces a compact microstrip antenna designed for versatile functionalities. The optimization of the antenna's performance is achieved by incorporating two angled strips and modified slots. The design includes a reduced ground plane and measures $15 \times 17 \times 16 \text{ mm}^3$. It operates over multiple frequency ranges, making it suitable for applications such as WLAN, satellite communications (including WiMAX (2350–8580 MHz)), IEEE 802.11a (54–57.525 GHz), and the 5G unlicensed band (2.5–7 GHz). Furthermore, the antenna is configured for network monitoring and radio system applications at 5.40 GHz, 6.76 GHz, and 8.2 GHz. Extensive simulations were conducted using High-Frequency Structure Simulator (HFSS) software, and a prototype was built to confirm the simulation results, showcasing the proposed design's effectiveness.

(Nair et al., 2019) presents a hexagonally-shaped frequency-adaptive patch antenna targeted at diverse applications, including WLAN, mobile satellite communication, and navigation. The antenna is constructed on an FR-4 substrate and measures $30 \times 40 \text{ mm}$ with a thickness of 1.58 mm. Its reconfigurable nature is facilitated by integrating two adjacent rectangular patch antennas with PIN diodes, allowing operation at different frequencies: 5.27 GHz, 2.16 GHz, 5.45 GHz, 2.88 GHz, and 5.76 GHz. When both diodes are activated, the antenna achieves a gain of 6.38 dBi and a bandwidth of 435 MHz. Simulations were performed using Ansys HFSS software, and a prototype was tested with a Keysight vector network analyzer to validate the simulation results.

(Glowacz et al., 2020) discusses a reconfigurable monopole antenna optimized for use in microwave frequency ranges with a low-profile design. The antenna operates in Mode 1 and Mode 2 at specific frequencies of 5 GHz and 3.5 GHz, respectively. Dual-band functionality is realized in modes 3 and 4, at frequencies of 2.6 GHz and 5.6 GHz. Additionally, it supports triple-band operation at 1.8 GHz, 4.8 GHz, and 6.4 GHz. Throughout all operational modes, the Voltage Standing Wave Ratio (VSWR) stays below 1.5. The antenna shows an efficiency of 84%, with gain values fluctuating between 1.2 and 3.6 dBi at the specified resonance frequencies.

(Pandya et al., 2020) emphasizes the significance of wireless communication for effective information exchange across distances. In this context, a multi-layered antenna has been developed, inspired by Split Ring Resonators (SRR) and materials exhibiting negative permeability. The antenna has undergone thorough analysis, fabrication, and experimental testing. It shows resonant frequencies at 1.13 GHz, 2.47 GHz, and 2.74 GHz, along with corresponding gain values of 3.73 dB, 6.18 dB, and 1.35 dB, respectively. The dimensions of the antenna are $40 \times 32 \times 1.6 \text{ mm}^3$, utilizing an FR4 substrate. The bandwidths achieved at these resonant frequencies are 2.10%, 2.81%, and 2.09%, respectively.

2.10.2. Brief of Studies Related to 6G Satellite Applications

(Ahmad et al., 2019) investigates the design of planar, high-efficiency on chip antennas specifically tailored for operation at 165 GHz, with applications in integrated radar sensors. It evaluates several high performance planar antennas characterized within the D-band (110–170 GHz), all fabricated using FR4 material. Among the findings, a notable gain of 5 dBi was achieved with the LBE-based folded dipole antenna, which occupies a footprint of 1.88 mm^2 at 165 GHz. Additionally, the LBE patch antenna demonstrated an impressive gain of 6 dBi within a more compact area of 1 mm^2 at 160 GHz.

(Yi et al., 2020) details the development of frequency-modulated radar system using continuous wave technology that operates within the 220 to 320 GHz frequency range. The system employs a frequency comb architecture, realized using 65 nm CMOS technology. An innovative multi-resonant substrate-integrated waveguide antenna design is introduced, attaining a 15% fractional bandwidth to ensure effective impedance matched.. The frequency-comb design ensures that the

effective isotropic radiated power and noise figure remain stable, exhibiting minimal variation at 8.8 dB and 14.6 dB across a bandwidth of 100 GHz. The chip occupies a die size of 5 mm² and operates with a DC power consumption of 840 mW. To improve antenna directivity, a detachable, cost-effective TPX polymethylpentene lens, measuring 25.4 mm in diameter with a focal length of 10 mm, is positioned in front of the chip. This research represents a significant advancement in CMOS technology, achieving the largest bandwidth for radar systems operating above 200 GHz.

(Paun et al., 2022) introduces the engineering design of an innovative 6G antenna based on the Minkowski loop fractal. The authors utilized a square area antenna featuring corresponding fractal patterns to optimize the configuration of Minkowski's loop. Based on the methodologies outlined in the paper, the calculated fractal dimension is 1.465. The constructed and simulated fractal antenna measures $0.03 \times 0.028 \times 0.002$ mm³, exhibiting a gain of 3.13 dB at a primary directivity angle of 295°. The operational frequency ranges extend from 110 GHz to 170 GHz and from 170 GHz to 260 GHz; however, the authors did not provide further analysis regarding the antenna's performance characteristics.

(Mathivan and Rajeswari, 2022) shows a compact microstrip circular patch antenna specifically engineered for intelligent vehicle radar applications, operating at a frequency of 5.8 GHz within the C-band. The dimensions of the proposed antenna are $60 \times 35 \times 1.6$ mm³. Experimental results indicate a frequency range from 5.925 GHz to 5.728 GHz, with an S11 parameter measured at -19.56 dB. The antenna had a realized gain 8.20 dBi at 5.83 GHz, complemented by a directivity of 15.86 dBi and an omnidirectional bandwidth of 197 MHz. However, the authors did not provide additional performance analysis for the antenna.

(Nissanov and Singh, 2023) details a three steps design for a coplanar waveguide array antenna that incorporates via-holes, targeting operation at frequencies exceeding 100 GHz. The antenna radiate frequency range of 107.41 to 133.54 GHz, featuring dimensions of $15 \times 12 \times 0.127$ mm³ and achieving a peak gain of 12.98 dBi. A return loss of -28.802 dB was recorded. The patch radiator is fabricated using Rogers RO3003 material, with thickness of copper material 17.5 µm and a substrate height of 127 µm.

3. MATERIALS AND METHODS

3.1. Software Requirements

In the project, CST and HFSS design programs were utilized for antenna design, modelling, and analysis. The simulation of the control card for the reconfigurable antenna was conducted using ADS software. Altium Designer was utilized for the circuit design and PCB layout of the prepared control card.

3.1.1. Altium Designer

Altium Designer, a popular tool for designing Printed Circuit Boards (PCBs), serves the purposes of schematic creation, PCB layout, and generating production files. It also provides cloud-based infrastructure support through Altium 365, enabling collaboration on the same project.

3.1.2. CST Studio Suite

CST Studio Suite is a widely used software for electromagnetic field simulations in microwave design engineering, allowing for the design and evaluation of components such as antennas, transmission lines, and resonators. It supports complex 3D solid modeling and enables analyses such as electromagnetic field distribution at various frequencies, S-parameter evaluations, and more. The software incorporates various numerical methods to achieve accurate simulations, including the Finite Element Method (FEM) for solving complex geometries, the Finite Integration Technique (FIT) for electromagnetic field calculations, the Method of Moments (MoM) for efficient evaluation of radiation problems, and the Transmission Line Matrix (TLM) method for time-domain simulations. These methods provide versatility and precision, making CST suitable for analyzing diverse electromagnetic design challenges (Dassault systemes, 2019).

3.1.3. High Frequency Structure Simulator

HFSS is a three-dimensional electromagnetic field simulation application designed for virtual prototyping and development, enabling analyses such as electromagnetic field distribution at various frequencies, S-parameter evaluations, and other performance metrics for designed virtual prototypes. Similar to CST Studio Suite, HFSS employs advanced numerical methods to ensure precise simulations, including the Finite Element Method (FEM) for solving complex 3D geometries, the

Integral Equation (IE) method for efficient radiation and scattering problems, and the Hybrid Finite Element-Boundary Integral (FE-BI) technique for handling open-region problems. These numerical approaches provide robust solutions for analyzing and optimizing high-frequency designs across various engineering applications (Ansys, 2024).

3.1.4. Advanced Design System

ADS program created by Keysight Technologies for RF and microwave circuit design, electromagnetic field simulations, and analyses. The accuracy and performance of the designed RF circuit can be tested.

3.2. Hardware Requirements

3.2.1. Rogers RT 5880

Rogers RT 5880 is a PTFE composite enhanced with glass microfibre, possessing a dielectric constant of 2.2. Its lower dielectric constant in relation to standard FR4 composites makes it favourable for high-frequency RF and microwave applications. RT 5880 has a loss tangent value of 0.0009 at 10 GHz. The properties of the hardware material are given in Table 3.1 (Rogers Corporation, 2022).

Table 3.1. Physical characteristics of the Rogers RT 5880 material

Material	Relative Permittivity	Relative Permeability	Conductivity (S/m)
RT 5880	2.2	1.0	2×10^7

3.2.2. Copper

Copper is preferred due to reasons such as strength, fatigue resistance, electrical conductivity, thermal conductivity, corrosion resistance, and ease of manufacturing. The characteristics of the hardware material are detailed in Table 3.2. (Parchin et al., 2020).

Table 3.2. Physical characteristics of copper material.

Material	Relative Permittivity	Relative Permeability	Conductivity (S/m)
Copper	1.0	1.0	58×10^6

3.2.3. Flame Retardant - 4

FR-4 is a foundational material composed of glass fiber and epoxy resin, which is flame-resistant. Its dielectric constant varies between 3.8 and 4.8 according to production standards. The characteristics of the hardware material are outlined in Table 3.3. (Parchin et al., 2020).

Table 3.3. Physical characteristics of the FR-4 material

Material	Relative Permittivity	Relative Permeability	Conductivity (S/m)
FR-4	4.4	1.0	3.4×10^9

3.2.4. Electronic Components

Electronic components are the fundamental building blocks used in the creation of circuits. They are categorized into two primary types: passive and active. Passive circuit elements can either expend or store energy. Examples of passive circuit elements include resistors, inductors, and capacitors. Active circuit elements, on the other hand, are electronic components that require external energy to perform their functions and consist of at least two or more materials. Examples of active components include transistors, diodes, and thyristors (Parchin et al., 2020).

3.2.5. RF Switch

GMP4201 is a PIN diode developed using standard plastic package technology, featuring 0.5nH parasitic inductance and 0.07pF parasitic capacitance. It offers broadband performance up to 5 GHz, with a maximum total capacitance of 0.18pF. In the forward bias condition, the series resistance measures 2.3 Ohms at 1mA and 1.2 Ohms at 20mA. The carrier lifetime is 100ns. It is appropriate for uses including RF and microwave switching, attenuators, and limiters. Figure 3.1 shows the GMP4201 3D view and pad layout (Microchip, 2009).

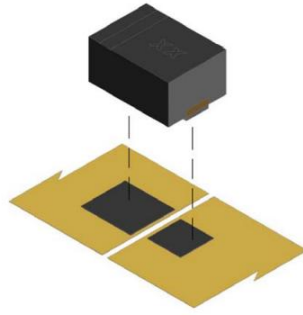


Figure 3.1. GMP4201 3D view and pad layout (Microchip, 2009)

3.2.6. EMI Shielding Sheets

EMI copper foil shielding tape is a type of adhesive tape used to provide Electromagnetic Interference (EMI) shielding in electronic devices and circuits. Figure 3.2 shows the foil protective tape (Würth, 2023).



Figure 3.2. EMI copper foil shielding (Würth, 2023)

This tape is designed to prevent or redirect electromagnetic interference that could disrupt proper operation in electronic devices or circuits, or lead to unwanted signals. By applying copper foil tape to specific areas or components, it helps to control electromagnetic radiation and prevents it from interfering with sensitive circuits. Foil shielding offers a higher coverage area compared to braided shielding, but it is less flexible and may be more prone to damage if the cable needs to be bent or flexed frequently. The copper foil tape used in the prepared prototype is the product coded 3003350A produced by Würth Electronics (Würth, 2023).

3.2.7. SMA Connector

This is the standard male Sub Miniature Version A (SMA) connector. SMA connectors have an impedance of $50\ \Omega$. Also, it is a type of screw-type coaxial connector usually used in microwave systems and mobile telephone antennas as shown in Figure 3.3 (Microchip, 2009).



Figure 3.3. Standard connector SMA (Microchip, 2009)

3.3. Microstrip Antenna Design Methodology

Designing an antenna that is compact yet offers wide bandwidth, high gain, and low return loss presents a significant challenge. Computer simulation software plays a crucial role in this process. Microwave Studio, a leading tool for time-domain simulation, is particularly valuable for accurately modelling devices in three dimensions at high repetition rates. This software enables efficient analysis of radio channels, links, couplers, multilayer structures, signal integrity, and electromagnetic compatibility. Among the different types of antennas, microstrip patch antennas are notable for their compact size, slim profile, simplicity in fabrication, ease of integration, and affordability. By carefully positioning slots in the antenna design, it is possible to attain outstanding performance regarding bandwidth, resonant frequency, gain, impedance, and return loss. Additionally, precise impedance matching is essential during the design of microstrip patch antennas, while appropriate feeding techniques are employed to provide the necessary input to the antennas. The radiation patterns of the antenna can be effectively analysed using computer simulation technologies such as CST, HFSS, and ADS.

For the analysis of microstrip antenna, there are various methods available, including the transmission line model, cavity model, and full wave mode. As a popular and simplest method among the above-mentioned models, we have used transmission-line mode. The effective width and length of the proposed antenna substrate were determined utilizing Equations (3.1 - 3.4), which are derived from the operating resonance frequencies pertinent to the intended applications. In these

equations, C denotes the speed of light, f_r signifies the resonance frequency, W_p represents the substrate width, L indicates the substrate length, ϵ refers to the effective permittivity, L_{eff} represents the effective length, and ϵ_r represents the relative permittivity. The characteristic impedance of a microstrip antenna is a crucial parameter that affects its performance. It is determined by the configuration of the microstrip line, including the conductor's width and the characteristics of the substrate material, which can be computed using Equations (3.5, and 3.6) (Nguyen, 2016).

$$W_p = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (3.1)$$

The effective permeability (ϵ_{eff}) is determined using Equation (2), which considers the substrate thickness and width.

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{w_p} \right]^{-\frac{1}{2}} \quad (3.2)$$

The extension length (ΔL) of the microstrip patch antenna was determined using Equation (3.3).

$$\Delta L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{w_p}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{w_p}{h} + 0.8 \right)} \quad (3.3)$$

The length (L) of the microstrip patch antenna was determined using Equation (3.4).

$$L = \frac{c}{2f_r \sqrt{\epsilon_{\text{reff}}}} - 2\Delta L \quad (3.4)$$

$$z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \left(\frac{8h}{w} + \frac{w}{4h} \right) \quad , \text{ if } \frac{w}{h} \leq 1 \quad (3.5)$$

$$z_0 = \frac{120\pi}{\sqrt{\epsilon_r}} \left[\frac{h}{w + 1.393 + 0.667 \ln \left(\frac{w}{h} + 1.444 \right)} \right] \quad , \text{ if } \frac{w}{h} > 1 \quad (3.6)$$

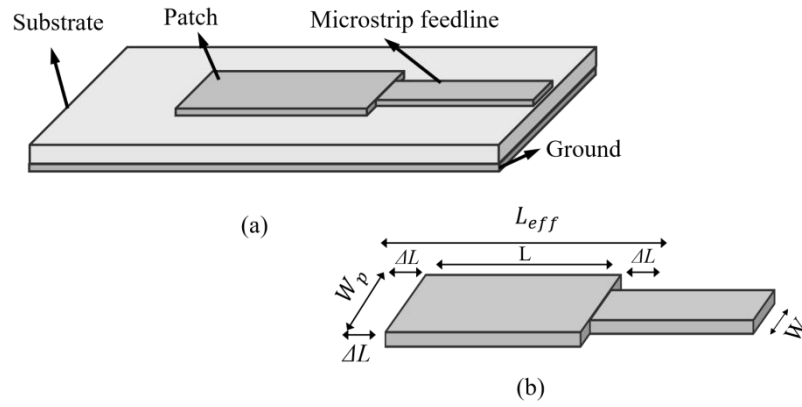


Figure 3.4. a) Microstrip patch antenna, b) Plan view of the patch antenna (Nguyen, 2016)

The co-planar wave-guide utilized in this study is a sophisticated planar transmission line specifically designed for signal transmission at microwave frequencies. This configuration comprises a single conductor strip situated on a dielectric substrate, flanked by ground planes on either side, which allows all conductors to exist within the same plane—a characteristic denoted by the term "co-planar." In comparison to microstrip lines, CPWs offer notable advantages, including a compact design, reduced weight, and minimized transmission losses. The design of CPW-fed antennas is constrained by three critical parameters: the resonance frequency (f_r), the substrate's dielectric material, and the substrate thickness (t). Notably, a thinner substrate not only reduces the total footprint of the antenna but also mitigates the generation of surface waves. Moreover, substrates with low dielectric constants facilitate broader bandwidths, enhanced efficiency, and lower power loss, rendering CPWs particularly advantageous for microstrip antenna designs. The characteristic impedance of the CPW is contingent upon several factors, including the feeder strip's width (w), the spacing between the ground sides (s), the thickness of the substrate (h), and substrate's dielectric constant (ϵ). This impedance can be determined using Equation 3.7. Additionally, the electric field lines, illustrated as dashed lines in the accompanying figures, are concentrated between the conductor strip and the ground planes. These lines demonstrate how charges on the conductor strip are directed towards the ground strips, thereby generating an electric field. In contrast, the magnetic field lines, indicated by dashed arrows, surround the conductor strip and represent the magnetic field generated by the current passing through it, as shown in Figure 3.5 (Nguyen, 2016)

$$Z_0 = \frac{60}{\sqrt{\epsilon_{\text{eff}}}} \times \ln \left(\frac{4h}{\pi(w+2s)} \right) \quad (3.7)$$

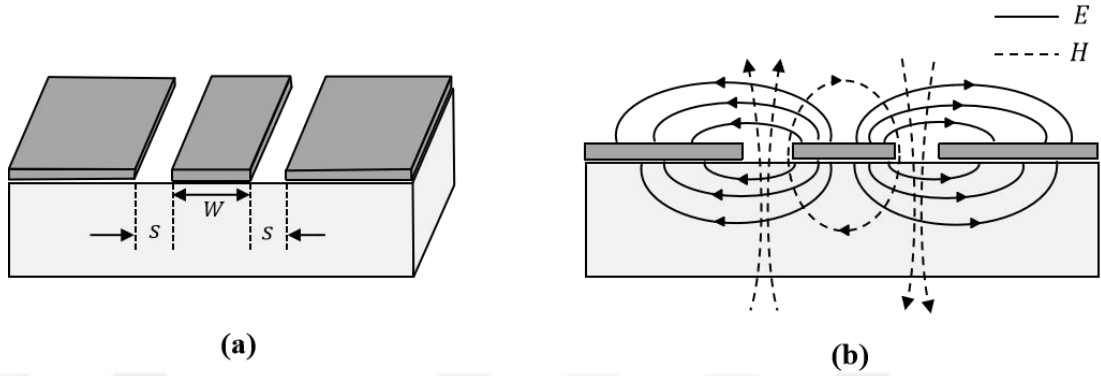


Figure 3.5. a) CPW structure, b) E,H fields interactions (Nguyen, 2016)

3.4. Microstrip MIMO Antenna Design Methodology

The antenna design process was executed in three distinct stages: the single-element configuration, followed by two-element or four-element configurations. This phased approach is critical for enhancing performance, facilitating design optimization, and managing implementation costs effectively. In MIMO systems, augmenting the number of antenna elements greatly enhances data transmission speeds and improves signal quality. Each additional element enhances system capacity and performance, thereby accommodating the demands of more complex and densely populated data communication environments. Conducting the design in incremental stages allows for the evaluation and optimization of performance outcomes at each phase. This methodology enables the identification and rectification of potential design flaws early in the process. However, it is essential to recognize that the integration of additional antenna elements may lead to increased manufacturing costs and complications in physical layout and integration. Thus, beginning with a little number of elements in the initial stages of design promotes efficient utilization of the project budget and time-line, ensuring that costs remain controlled and the design process manageable.

Isolation refers to the technique employed to minimize electromagnetic interference between antenna elements in a MIMO system. In configurations with multiple antennas operating in concert, unwanted signal transients may arise between

the elements, known as near-field coupling, which can detrimentally impact antenna performance. To mitigate this coupling, effective isolation strategies are implemented. The isolation between antennas is determined by calculating the appropriate distances between MIMO antennas, which is typically set at half the wavelength, as expressed in Equation 3.8.

$$\frac{\lambda}{2}, \lambda = \frac{c}{f} \quad (3.8)$$

This strategic spacing is essential for maintaining optimal performance in MIMO systems.



4. FINDINGS AND DISCUSSION

This chapter discusses the design of two unique types of antennas customized for particular communication purposes. The first antenna is intended to function within standard satellite frequency bands, adhering to the established guidelines that ensure dependable communication in current satellite systems. In contrast, the second antenna design focuses on the emerging 6G frequency bands, which are anticipated to support next-generation communication technologies. Through detailed analyses of both designs, this chapter aims to highlight the unique challenges and considerations associated with each frequency range, ultimately contributing to advancements in antenna technology for various communication needs.

4.1. Antenna Design for Regular Satellite Frequency Bands

The patch configuration of this microstrip antenna design is made from annealed copper, with the substrate material being Rogers RT5880, noted for having a 2.2 relative permittivity of and 0.508 mm thickness (Rogers Corporation, 2022). Consequently, the antenna model is designed as a rectangular microstrip antenna with dimensions of $28.4 \times 30 \text{ mm}^2$. Figure 4.1 outlines the design steps of a proposed antenna model, where a co-planar waveguide is integrated into the top layer of the patch antenna, featuring a slotted circular feed line to enhance the bandwidth at the operating resonance frequencies. Frequency reconfiguration can be achieved by modifying the effective length of the patch antenna, which is done by adding radiators one positioned in the centre and another at the top of the antenna patch (Mabrouk, 2022). Additionally, end-fire reconfiguration of the radiation pattern is facilitated by incorporating radiators on the right and left flanks of the antenna patch. Throughout each design phase, S_{11} parameters were optimized, resulting in a final antenna model with dual resonance frequencies: one in the S-band and another in the X-band, as depicted in Figure 4.2.

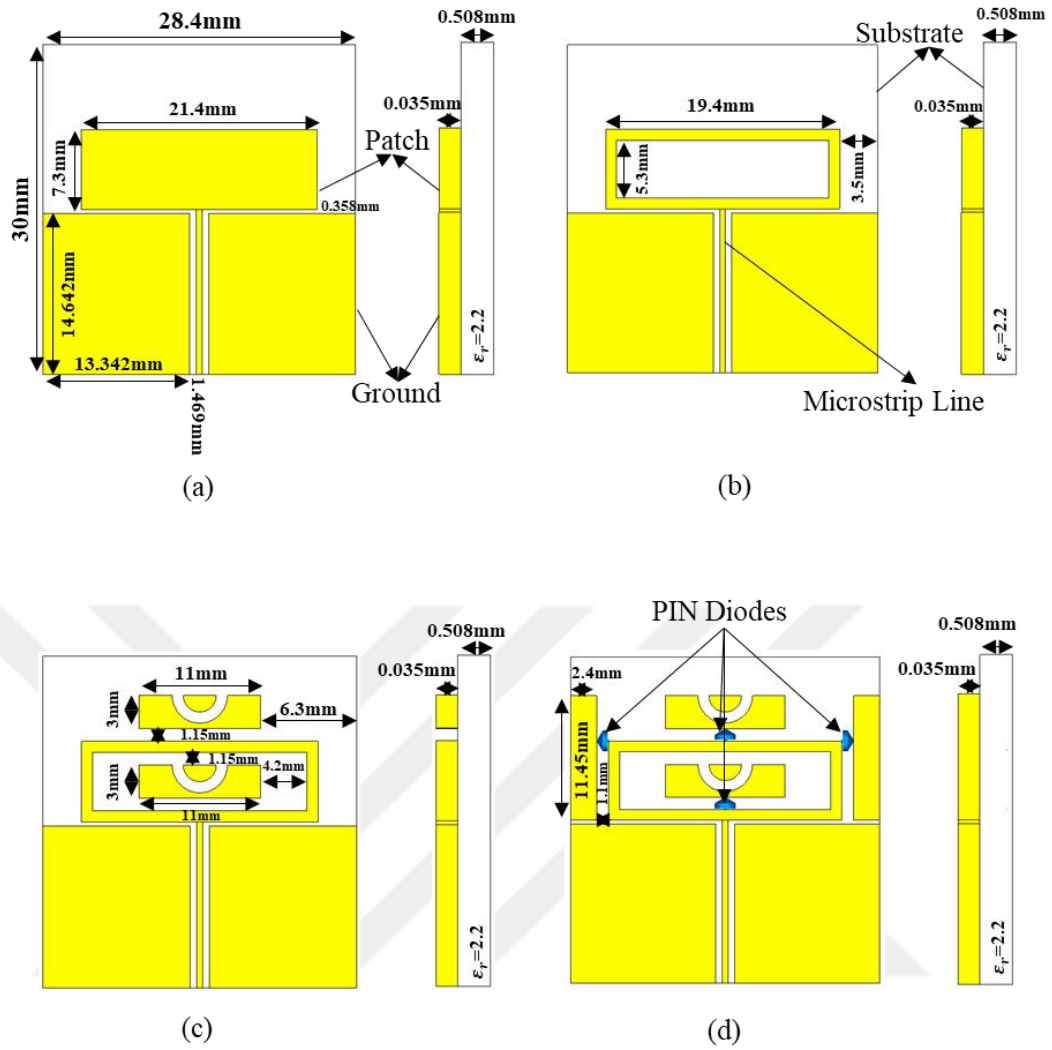


Figure 4.1. Antenna design steps, a) Step-I, b) Step-II, c) Step-III, d) Step-IV

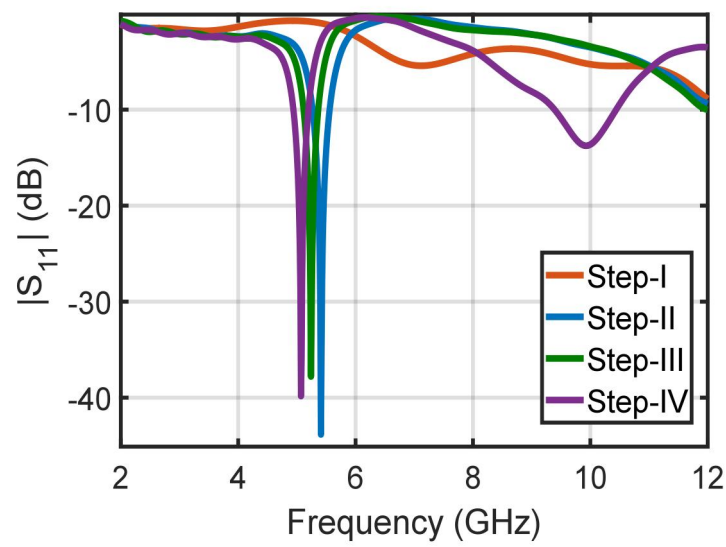


Figure 4.2. Simulated S_{11} results at different antenna geometries

4.1.1. Antenna Geometry Design and Analysis

Figure 4.3 illustrates the upper layer perspective of the antenna design, offering a comprehensive illustration of its structure. The co-planar distance S (illustrated by the dashed line in Figure 4.3) between the main feed line was refined using simulation software to achieve the optimal value, as depicted in Figure 4.4. Figure 4.5 presents the gain values corresponding to various gap distances between the feeder and the co-planar configuration and Figure 4.6 illustrates the overall efficiencies for various gap distances between the feeder and the co-planar setup.

A parametric optimization or design optimization was conducted using simulation based parameter sweeps to fine-tune the antenna's performance. This method involved systematically varying the co-planar gap distance S between the feeder and the antenna structure, with simulations conducted at each variation to evaluate key performance metrics. The optimization focused on minimizing the S_{11} parameter to achieve effective impedance matching while maximizing resonance efficiency and bandwidth. Among the tested gap distances ranging from 0.1 mm to 0.5 mm, the optimal value of 0.358 mm was identified as providing the best dual-band performance, with S_{11} values below -10 dB at the targeted resonance frequencies, as detailed in Table 4.1. To achieve this, a gradient-based optimization method was employed, utilizing mathematical models and advanced simulation tools like CST and HFSS to systematically evaluate and refine the antenna geometry. This comprehensive approach ensured precise tuning of design parameters to optimize the resonance frequency, efficiency, and overall antenna performance. Antenna operation frequency reconfiguration is achieved by mounting four different PIN diodes (Model: GMP 4201) that work as RF switches to pass the RF signals from patch to patch, altering the width and length of the overall antenna patch. The first PIN diode (D1) connects the centred slotted patch with the main feed line, while the second PIN diode (D2) connects the main feed line with the right rectangular patch; the third PIN diode (D3) links the main feed line with the top slotted patch; and the fourth PIN diode (D4) connects the main feed line with the left rectangular patch. All PIN diodes are represented by lumped elements in the simulation programs, as shown in the antenna structure in Figure 4.7.

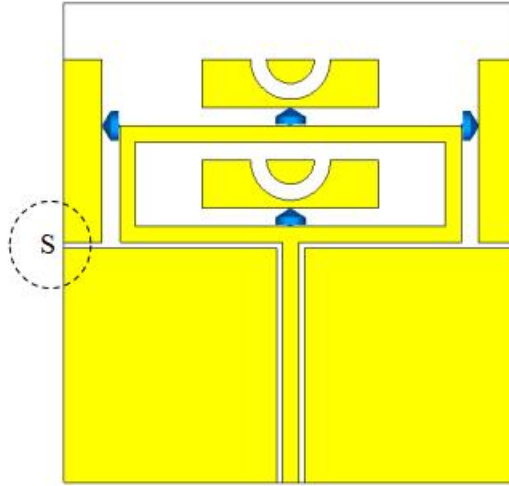


Figure 4.3. Space gap of antenna Geometry

Table 4.1. Gap selection gain and efficiency analysis

S (mm)	Frequency (GHz)	Gain (dBi)	Efficiency (%)
0.10	5.07	4.6	87
0.15	5.07	4.7	85
0.20	5.07	4.8	81
0.40	5.07	4.8	70
0.50	5.07	4.9	67
0.358	5.07	5.1	89

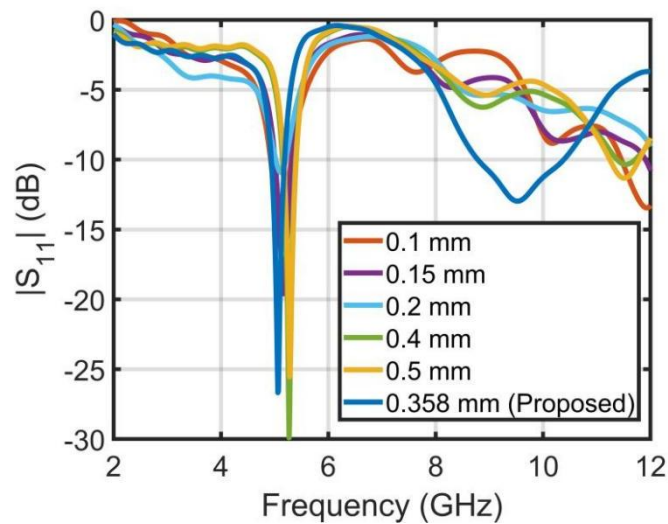


Figure 4.4. Simulated S_{11} parameter of the proposed antenna configuration at various gap distances.

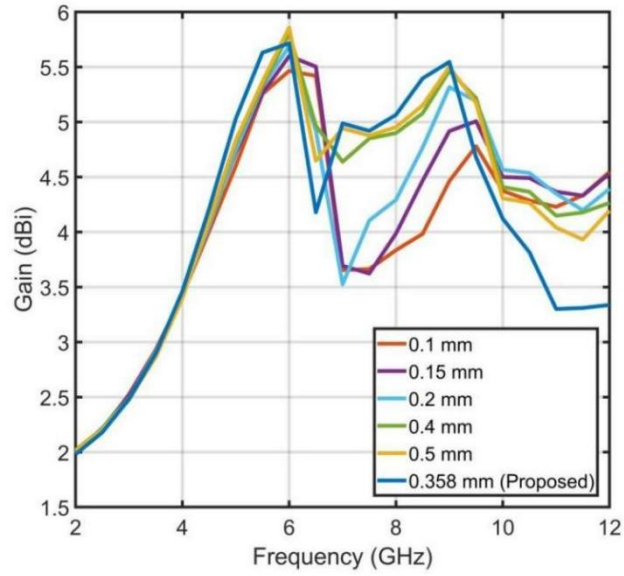


Figure 4.5. Gain values at different gap distances between feeder and co-planner

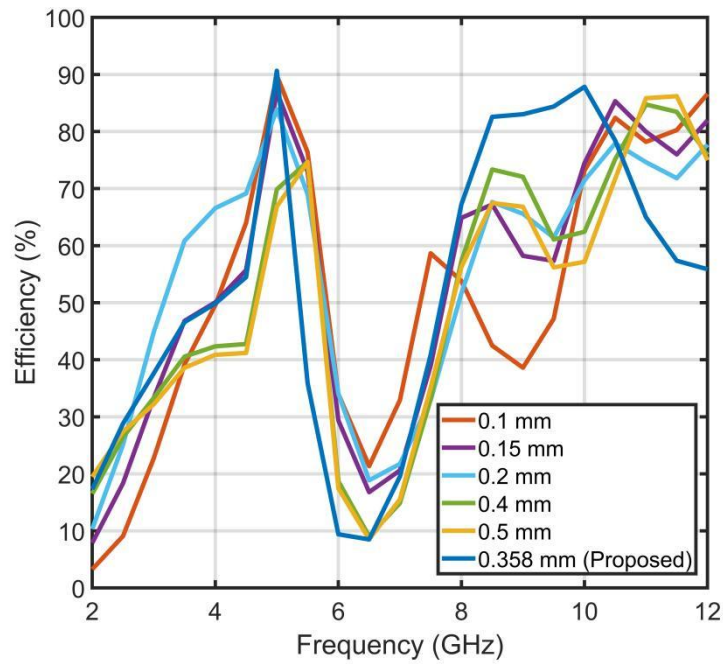


Figure 4.6. Total efficiencies of different gap distances between feeder and co-planner

4.1.2. PIN Diodes Selection Analysis

The design incorporates four PIN diodes to facilitate frequency reconfiguration. One diode (D1) connects the patch to the center-slotted rectangular radiator, while another diode (D3) attaches the antenna patch to the top-slotted radiator. The remaining two diodes (D2 and D4) establish links with the left and right radiators, as well as the central patch, as shown in the 2D antenna model in Figure 4.7. When in

the active state, each PIN diode operates as a combination of an inductor (L) and a resistor (R) in series. In contrast, when inactive, it functions as a parallel configuration of resistance (R) and capacitance (C), along with an associated series inductor. During CST simulations, these components are modelled as lumped RLC elements. Figure 4.8 illustrates the physical equivalent circuit of the PIN diode, and Table 4.2 presents the parameters for resistance, capacitance, and inductance specific to the PIN diode model (GMP4201) in both active and inactive states. When the capacitor is switched off, it effectively halts current flow, creating an open circuit that characterizes the OFF state of the PIN diodes. The positioning of each PIN diode is determined based on the targeted operating frequency. The switching time of the GMP4201 PIN diode is a critical parameter that enables rapid transitions between its "ON" (conductive) and "OFF" (non-conductive) states, optimized through its design. The diode features a thin intrinsic layer with optimal thickness, which minimizes the time required for charge carriers to clear or build up, ensuring rapid depletion and recovery during state changes. Additionally, its low minority carrier lifetime allows for quick recombination of charge carriers, reducing delays, while the minimized reverse recovery time ensures swift cessation of conduction under reverse bias. With a fast response time of 100 nano-seconds (Tan et al., 2013).

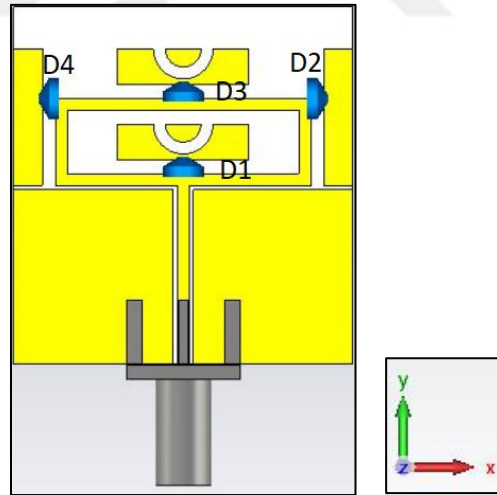


Figure 4.7. 2D view of the proposed antenna with PIN diodes

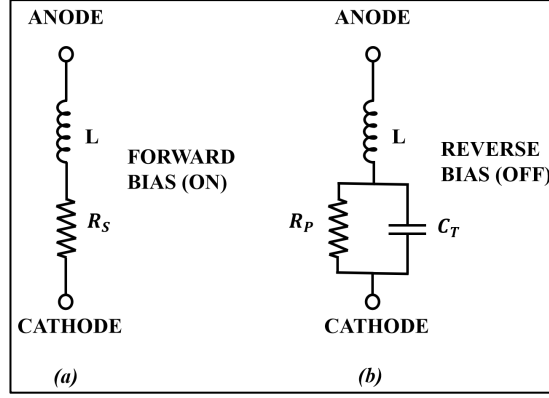


Figure 4.8. PIN diode electrical representation: a) Conducting state, b) Non-conducting state (Tan et al., 2013)

The analysis of the PIN diode also includes how variations in capacitance and inductance affect its performance. As depicted in Figure 4.9, the inductance (H) in the lumped equivalent circuit of the proposed PIN diode shows that increasing the inductor value leads to a shift of the frequency band to the right on the S_{11} graph, suggesting an increase in frequency. Conversely, Figure 4.10 reveals the impact of changes in capacitance (F) on the lumped equivalent circuit. An increase in the capacitor value results in the frequency band moving to the left on the S_{11} graph, indicating a reduction in frequency.

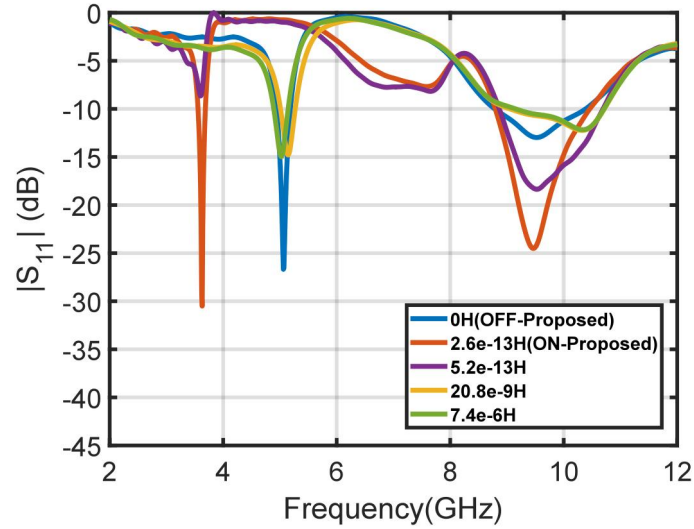


Figure 4.9. PIN diode behaviour with different inductor values

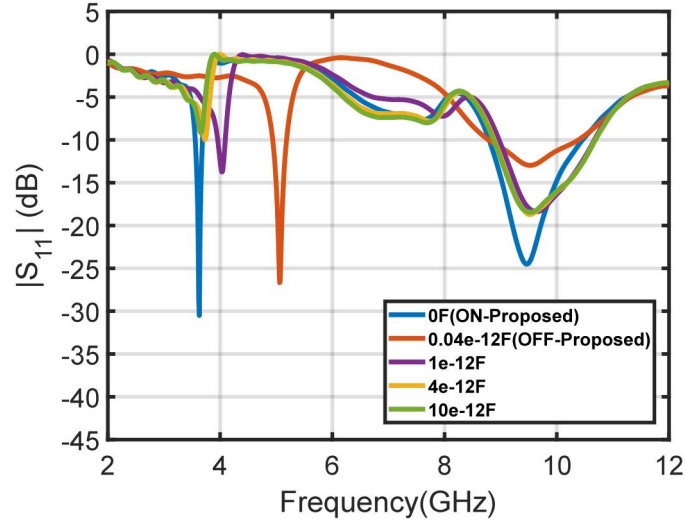


Figure 4.10. PIN diode behaviour with different capacitor values

The proposed PIN diode selected after analysis with another diode models (HPND4005, and MACom MA46BL912) that used in the previous works, the physical properties of the each diode model shown in Table 4.2. Figure 4.11 shows that the three diode models have similar performance over the 5.06 GHz frequency band but the performance over the 9.52 GHz are different. HPND4005 diode has resonance frequency of 11.02 GHz and MACom MA46BL912 diode has resonance frequency of 10.93 GHz under -10 dB. While Figure 4.12 shows that the GMP4201 has highest gains of the proposed two resonance frequencies (5.06 GHz, and 9.52 GHz) more than 5.5 dBi. Figure 4.13 shows that the GMP4201 has total efficiencies around the 90% which are higher than the other diode models.

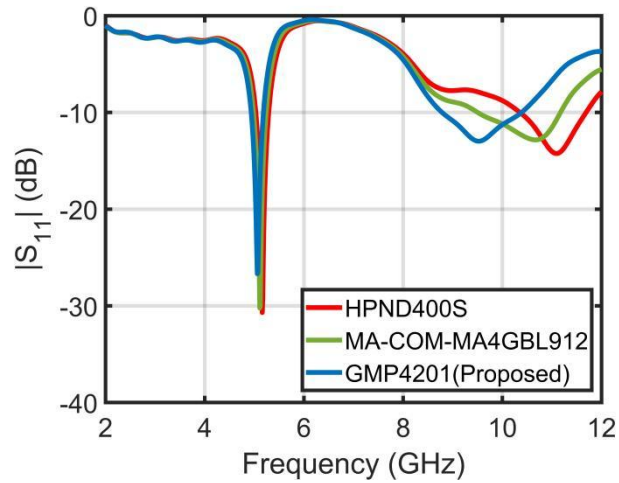


Figure 4.11. S_{11} parameter of different PIN diode models

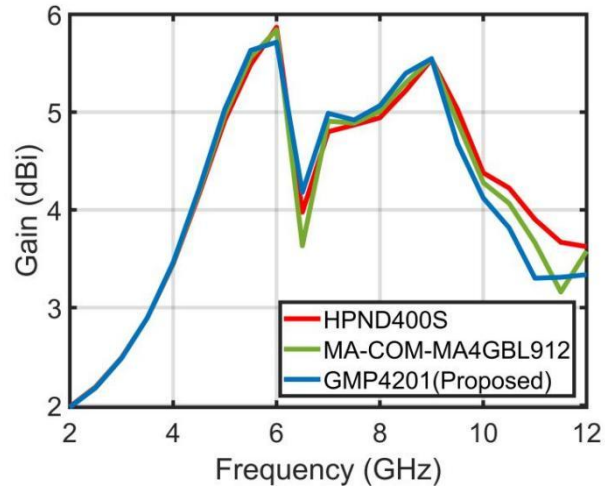


Figure 4.12. Gain over frequency of different PIN diode models

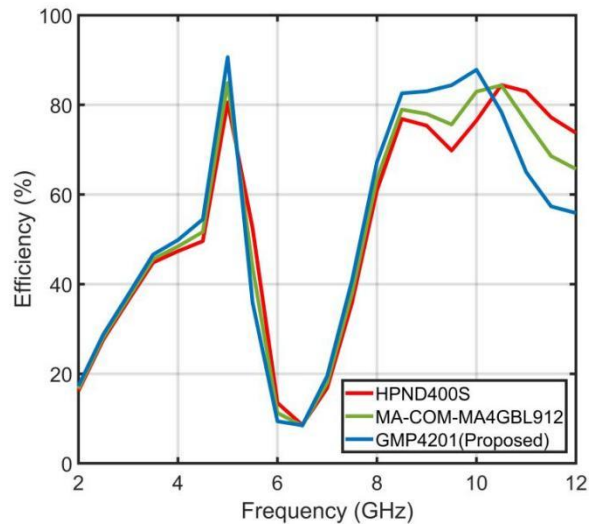


Figure 4.13. Total efficiency over frequency of different PIN diode models

Table 4.2. RLC values of the PIN diode equivalent circuit

Models	State	Resistance (Ω)	Inductor (H)	Capacitor (F)
GMP4201	ON	3	2.6 p	0
	OFF	20 k	0	0.04 p
HPND4005	ON	4.7	450 p	0
	OFF	10 k	0	0.017 p
MACom MA46BL91 2	ON	4.2	0.5 n	0
	OFF	10 k	0	0.028 p

4.1.3. PIN Diodes Control Unit Design

Diodes biasing is achieved by designing one control unit with four different switches, each controlling the enabling and disabling of the PIN diodes. Additionally, two capacitors are used at the input and output of each PIN diode to prevent mixing between RF signals and DC signals, and a protection circuit is added at the DC voltage source of the circuit. Figure 4.14 illustrates the schematic circuit of the control unit created using the Altium circuit design program.



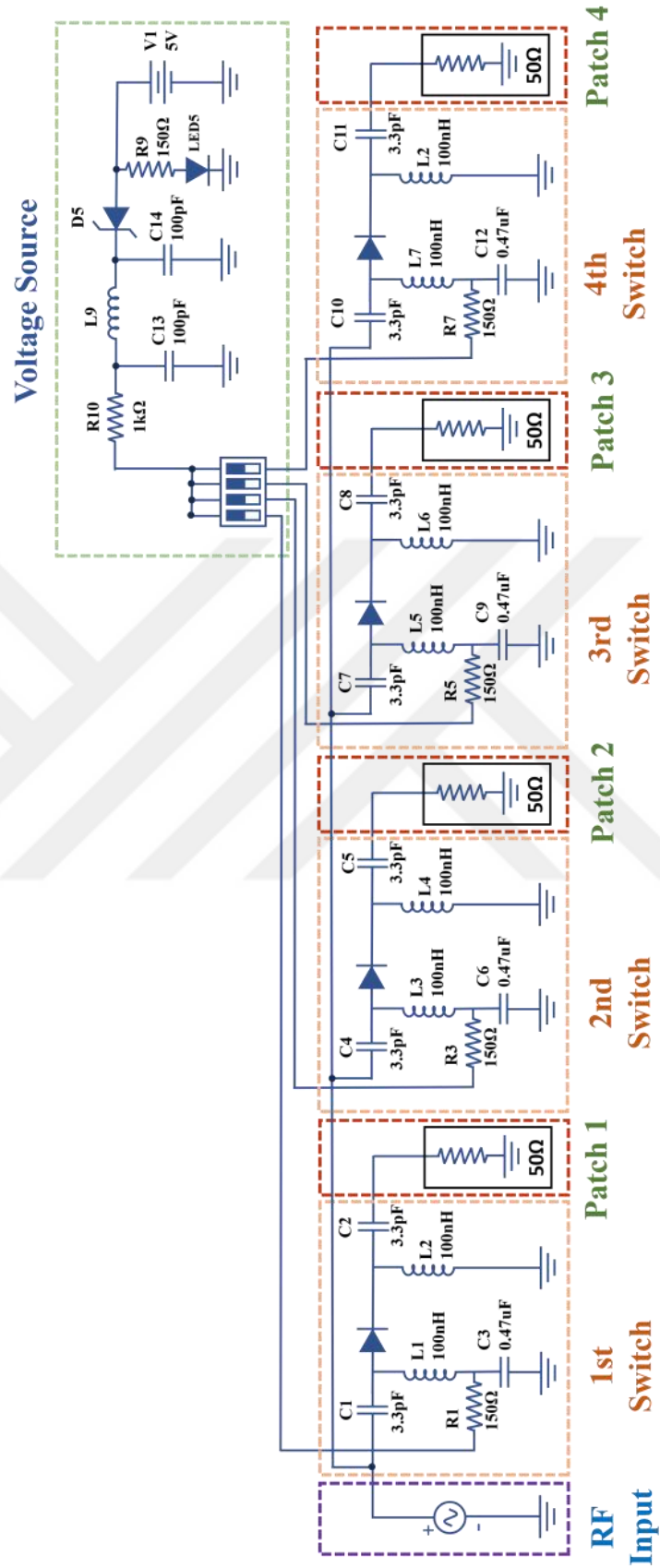


Figure 4.14. Schismatic of the PIN diodes control unit

4.1.4. Simulation Results of Antenna Model

Due to we have dual bands resonance frequencies, one of them wide band and another one is narrow band, this antenna geometry is verified by using two different microwave simulation program CST and HFSS. Using both tools allows validation of the antenna's performance across different operating scenarios and ensures robustness in real-world applications. CST is primarily uses FIT for time-domain simulations but also supports frequency domain solvers, eigenvector solvers, and other specialized solvers. Furthermore, Time-domain solvers are especially efficient for wideband simulations because they compute a wide frequency range in a single run. While HFSS based on the Finite Element Method (FEM), which is a frequency-domain technique, and FEM is very accurate for narrowband simulations and for problems involving complex geometries and high dielectric contrasts. The proposed antenna geometry verified over CST and HFSS simulation programs as shown in Figure 4.15, almost of the S_{11} parameter values are similar to the CST design over the two proposed resonance frequencies 5.06 GHz and 9.52 GHz as shown in Figure 4.16. Furthermore, the 3D views of the radiation pattern of the CST and HFSS almost similar to each other as shown in Figure 4.17 and 4.18. The antenna's symmetrical design complements this mode of operation, leverage its geometry and dielectric properties to support efficient bidirectional energy propagation. This dynamic behaviour demonstrates the antenna's adaptability to meet specific radiation requirements and frequency targets while maintaining high efficiency. also the values of the antenna gains and total efficiencies of CST and HFSS are around each other as shown in Table 4.3.

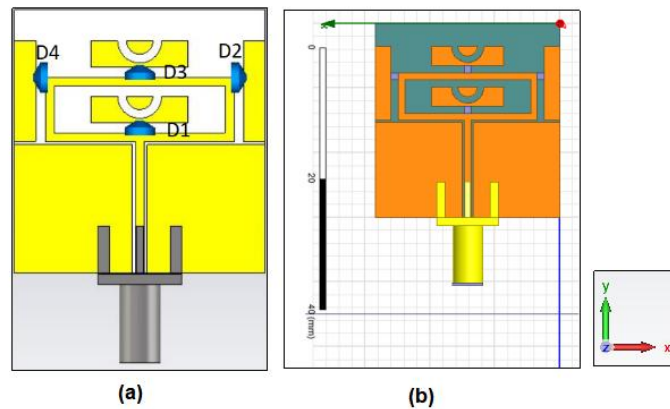


Figure 4.15. Recommended antenna design over a) CST b) HFSS

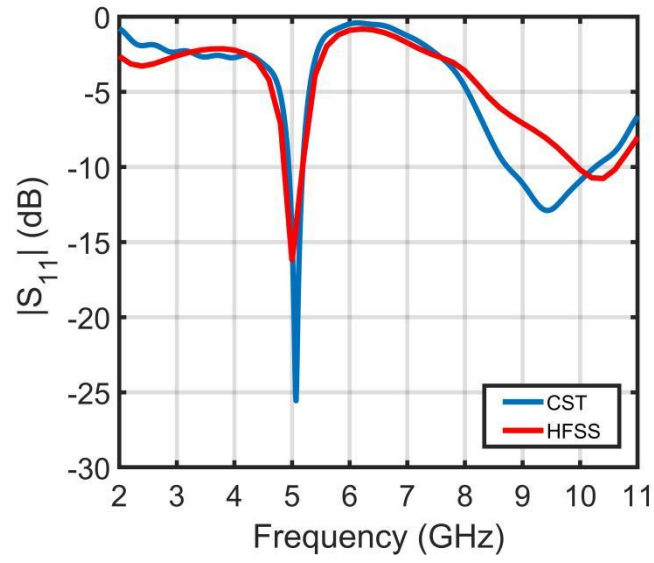


Figure 4.16. S_{11} parameter of the recommended antenna structure across simulation models

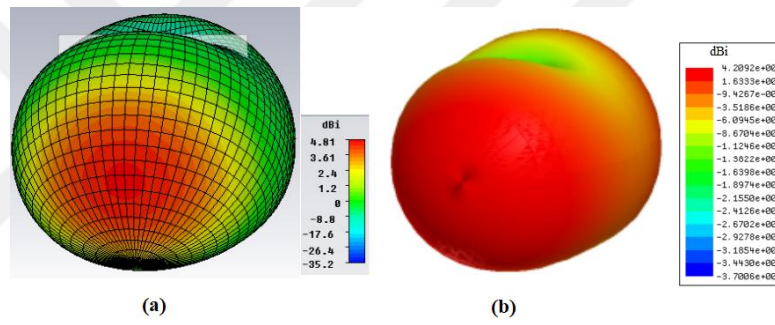


Figure 4.17. 3D form of radiation pattern, a) CST, b) HFSS at 5.06 GHz

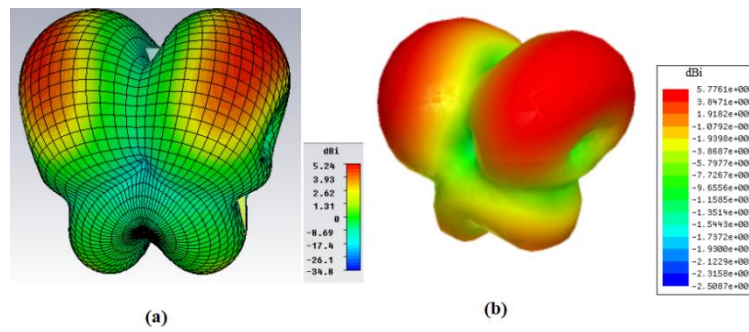


Figure 4.18. 3D form of radiation pattern, a) CST, b) HFSS at 9.25 GHz

Table 4.3. Gain and efficiency over CST and HFSS

Program	Frequency (GHz)	Gain (dBi)	Efficiency (%)
CST	5.06	4.81	91
	9.25	5.24	86
HFSS	5.06	4.787	97
	10.1	5.286	98

As shown in Table 4.3 the antenna achieves its exceptional theoretical efficiency of 98% by precisely managing the interaction between its structural components and operational parameters. Activating the D3 diode fine-tunes the impedance characteristics, leading to matching between the feed line and the radiating structure. This minimizes reflective losses and ensures optimal energy transmission. The activation also aligns the current distribution to form a balanced and bidirectional radiation pattern, which reduces energy dissipation and stabilizes the emitted signals. Additionally, the antenna's symmetrical design and the dielectric substrate's favorable properties collaboratively enhance energy propagation. This synergy between the diode control and the structural configuration enables the antenna to operate at peak efficiency, adapting to specific radiation and frequency demands seamlessly.

ADS program has tested the switching analysis of each PIN diode, as depicted in Figure 4.19, which is illustrated in Figure 4.20(a). The output RF signal passing through the PIN diode is similar to the input RF signal when the PIN diode is active, while the RF output signal is near zero when the PIN diode is disabled, as shown in Figure 4.20(b).

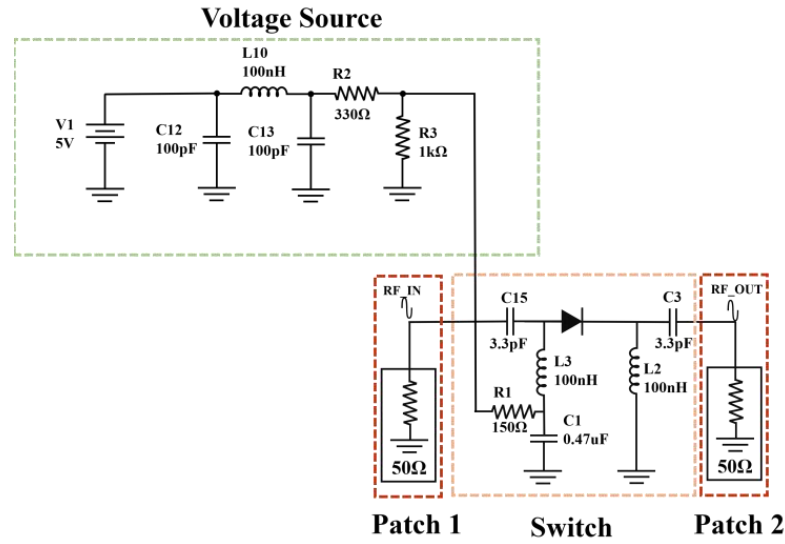


Figure 4.19. Schematic design of the control unit through ADS program

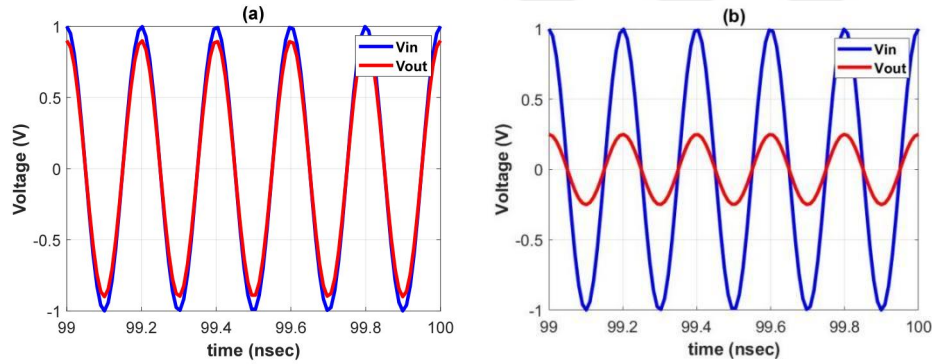


Figure 4.20. PIN diodes switching analysis results, a) PIN diode in active state, b) PIN diode in inactive state

To implement a reconfigurable antenna capable of operating across various frequencies, it is necessary to modify its electrical length and the current distribution. Therefore, four PIN diodes have been incorporated into the design. The ON-OFF states of these diodes are crucial as they dictate which frequency bands the antenna will utilize. The integration of PIN diodes facilitates alterations to the electric length of the radiating patch, enabling changes to the operational frequency without physically altering the patch's length. When the PIN diodes are biased, their resistance is minimal, allowing current to flow freely between different sections of the patch (creating a short circuit). Conversely, when the diode bias is removed, the resistance of the PIN diode increases significantly, preventing current from traversing through the diode gate (resulting in an open circuit).

As shown in Figure 4.21 while the first diode is activated the current flow starts to pass from the main circular feed line to the centred slotted patch, while the second diode is activated the current flow starts to pass from the main circular feed line to the right slotted patch, while the third diode is activated the current flow starts to pass from the main circular feed line to the top slotted patch, but once the fourth diode is activated the current flow starts to pass from the main circular feed line to the left slotted patch, this switching type causes the tuning of antenna resonance frequencies.

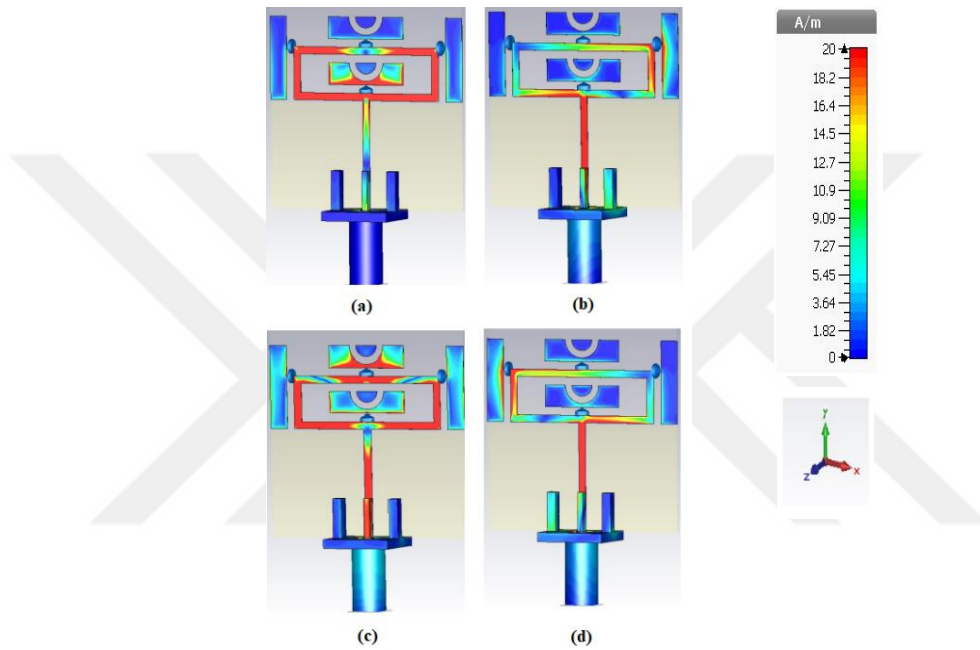


Figure 4.21. Current surface distributions over the proposed antenna design, a) D1 active, b) D2 active, c) D3 active, d) D4 active

The microstrip antenna design features four PIN diodes, allowing it to function across 16 unique operating modes, as shown in Figure 4.22. Each mode is associated with its own resonance frequencies corresponding to the S, C, and X satellite communication bands. The characteristics and properties of these 16 reconfiguration modes are summarized in Table 4.4, indicating the activation status of the PIN diodes marked as 1 for active and 0 for inactive. These operational modes are grouped based on the frequency bands they support (S, C, and X). The first group includes resonance frequencies within the S-band at 3.27 GHz, 3.45 GHz, and 3.54 GHz. This configuration can be achieved by activating diode D1 while keeping diodes D2 and D3 inactive along with the other diodes, which results in a gain of 3.9 dBi and an efficiency rating of 92%. The second group focuses on the C-band

frequencies, which range from 4.16 GHz, 4.57 GHz, 4.99 GHz, 5.07 GHz, 5.55 GHz, 6.29 GHz, to 7.3 GHz. These frequencies can be accessed by turning on diodes D2 and D3 while ensuring that the other diodes are turned off, yielding a maximum gain of 5.1 dBi and an efficiency of 98%. Lastly, the third group covers X-band resonance frequencies at 8.87 GHz, 9.78 GHz, 9.88 GHz, and 9.93 GHz, which can be reached by activating D1 while diodes D2 and D3 remain operational and the remaining diodes are deactivated, achieving a maximum gain of 5.084 dBi and an efficiency of 91%. However, a higher maximum gain of 6.34 dBi can be reached when the first (D1) and third (D3) diodes are active, while the other diodes are inactive. This significant gain enhancement can be attributed to the combined effect of optimized impedance matching, which minimizes energy reflection and enhances energy transfer; improved current distribution across the active diodes, resulting in a focused and efficient radiation pattern; reduced crosstalk and interference due to the deactivation of the other diodes, ensuring mode isolation; and the leveraging of the antenna's symmetrical design and geometry, which facilitates optimal energy utilization and directional radiation. These factors collectively enable the antenna to achieve superior performance at this operational mode.

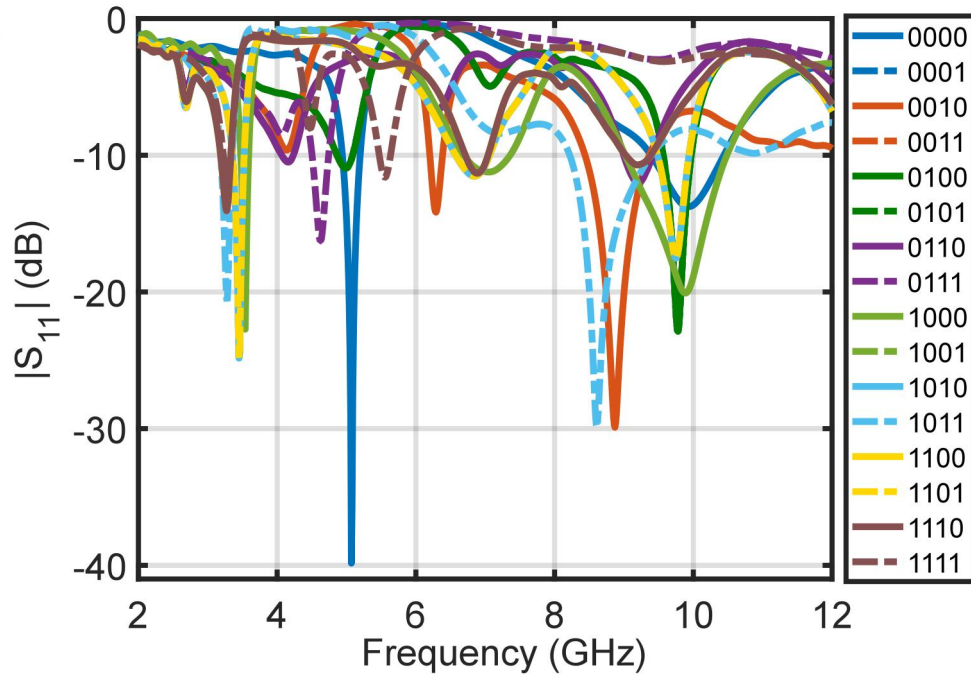


Figure 4.22. S_{11} parameters across different operating modes of PIN diodes

Table 4.4. Reconfigurable antenna performance across modes: frequency, S_{11} , gain, and efficiency analysis (simulation results)

Diodes				Frequency (GHz)	S_{11} (dB)	Gain (dBi)	Efficiency (%)
D1	D2	D3	D4				
0	0	0	0	5.07	-39.84	5.15	92.8
				9.93	-13.76	4.09	93.0
0	0	0	1	4.99	-10.94	4.27	93.0
				9.78	-22.88	5.08	91.5
0	0	1	0	6.29	-14.16	4.88	81.3
				8.87	-29.89	4.32	98.0
0	0	1	1	4.16	-10.49	3.81	90.3
				9.21	-12.02	4.54	93.6
0	1	0	0	4.99	-10.94	4.27	93.0
				9.78	-22.88	5.08	91.5
0	1	0	1	4.57	-20.72	4.22	85.3
				4.16	-10.49	3.81	90.3
0	1	1	0	9.21	-12.02	4.54	93.7
				4.4	-10.77	3.02	89.3
0	1	1	1	5.2	-23.27	2.56	89.5
				3.54	-22.72	3.97	87.9
1	0	0	0	7.05	-11.22	3.51	92.1
				9.88	-20.08	4.40	93.4
1	0	0	1	3.45	-24.84	3.12	85.3
				6.84	-11.52	3.58	92.4
1	0	1	0	9.75	-17.53	4.56	92.2
				3.28	-20.66	3.30	76.4
1	0	1	1	8.61	-29.91	6.34	84.7
				3.27	-14.06	3.18	84.4
1	0	1	1	6.89	-11.31	3.85	91.7
				9.2	-10.71	4.23	92.6
1	1	0	0	3.45	-24.84	3.12	85.3
				6.84	-11.52	3.58	92.4
1	1	0	1	9.75	-17.53	4.56	92.2
				3.43	-10.51	3.53	83.9
1	1	1	0	5.16	-31.44	5.11	84.4
				3.27	-14.06	3.18	84.4
1	1	1	1	6.89	-11.31	3.85	91.7
				9.2	-10.71	4.22	92.6
1	1	1	1	3.28	-11.62	3.31	88.0
				5.55	-14.06	4.38	84.7

The proposed microstrip antenna was tested as a receiver antenna, connected to Port 2 of a Vector Network Analyzer (VNA) around an anechoic chamber plates, while a reference antenna with a gain of around 10 dBi was placed 2 meters away and connected to Port 1 of the VNA. The measurement process involved collecting the S_{21} parameter, which represents the transmission coefficient between the antennas. The received gain was calculated using the Friis transmission equation and compared with the simulation results as shown in Figure 4.23. Figure 4.23 displays the polar form radiation patterns of the antenna model across various operational modes and resonance frequencies. Figure 4.23(a) and (b) shows the antenna demonstrates bidirectional patterns on both the E-plane and H-plane at 5.07 GHz, yielding an optimal gain of 5.158 dBi and a 92% efficiency when all PIN diodes are in the OFF configuration. While, the antenna performance metrics 3.39 dBi gain and 91% efficiency are noted with only the fourth PIN diode active and operates at 9.78 GHz as depicted in Figures 4.23(c) and (d). In Figures 4.23(e) and (f), the radiation pattern exhibits a bidirectional configuration at 8.87 GHz when the third PIN diode (D3) is active, while the others (D1, D2, D4) are inactive, resulting in a gain of 4.322 dBi and an efficiency of 98%. This performance is achieved due to the precise control over the antenna's operational mode, where activating D3 optimizes the radiating structure's impedance, ensuring efficient energy transfer and minimizing losses. The selective activation of D3 creates a uniform current distribution tailored for bidirectional radiation, which reduces dissipation and enhances stability in the radiation pattern. Furthermore, the antenna's symmetrical design complements this mode of operation, leveraging its geometry and dielectric properties to support efficient bidirectional energy propagation. This dynamic behavior demonstrates the antenna's adaptability to meet specific radiation requirements and frequency targets while maintaining high efficiency.

Also, as shown in Figures 4.23(g) and (h), deactivating the second PIN diode while the others remain active results in bidirectional patterns at 6.89 GHz, with notable gains of 3.5 dBi and an efficiency of 91.7%. Finally, Figures 4.23(i) and (j) reveal that bidirectional patterns are maintained at 3.54 GHz, with peak gains of 3.977 dBi and a remarkable efficiency of 87.9%.

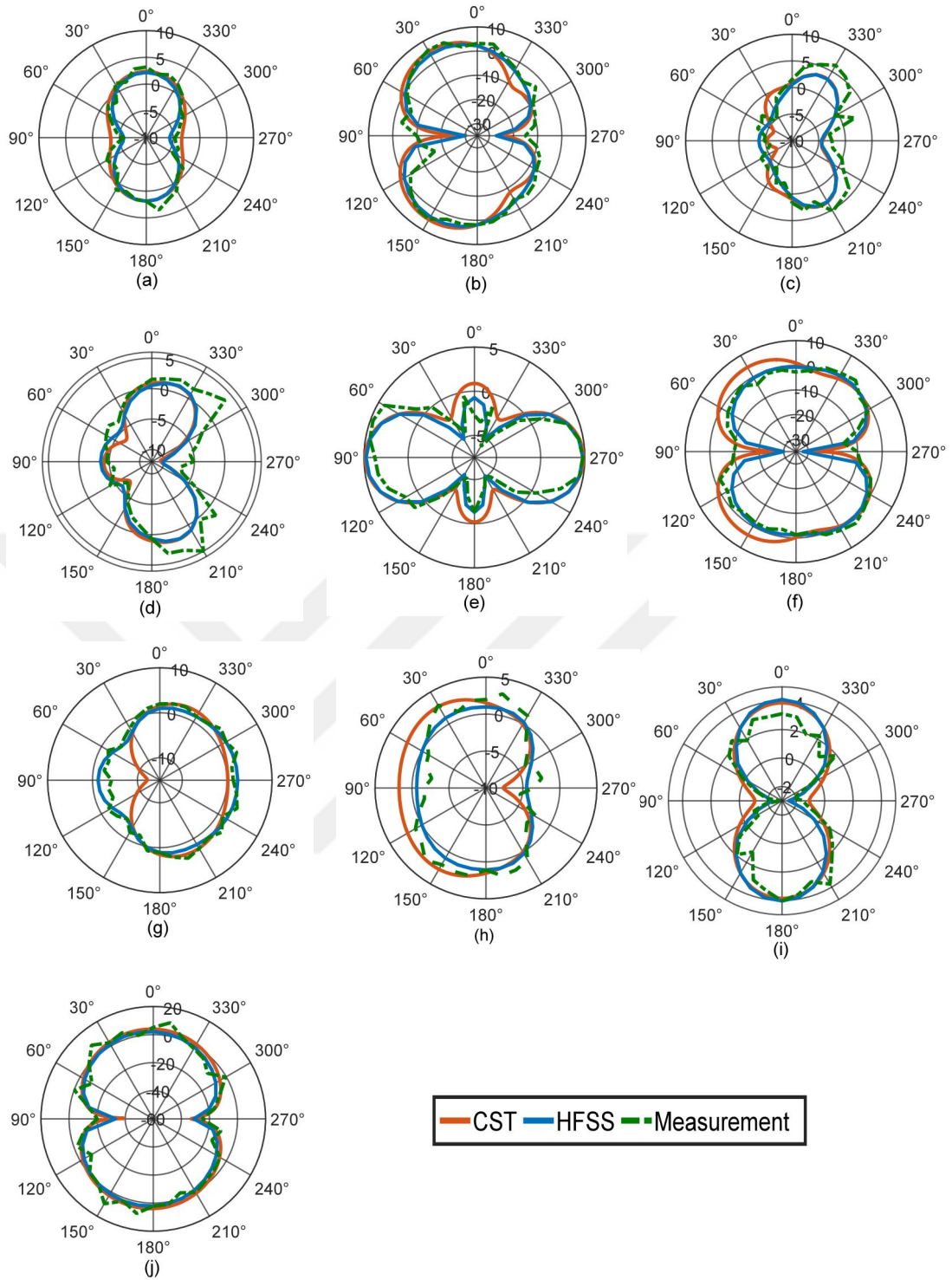


Figure 4.23. Polar form of the recommended antenna patterns at, a) 5.07 GHz E-plane, b) 5.07GHz H-plane, c) 9.78GHz E-plane, d) 9.78GHz H-plane, e) 8.87GHz E-plane, f) 8.87 GHz H-plane, g) 6.89 GHz E-plane, h) 6.89GHz H-plane, i) 3.54GHz E-plane, j) 3.54GHz H-plane.

As shown in Figure 4.21 while the first and fourth diodes activated the current flow starts to pass from the main circular feed line to the left and centred patches and that redirect the antenna radiation pattern to the left edge but the activation of the first and second diodes allow to pass to current flow from the main circular feed line to the right and centred patches and that redirect the antenna radiation pattern 180 degree to the right edge as shown in Figure 4.24. This switching type causes the tuning of antenna resonance frequencies.

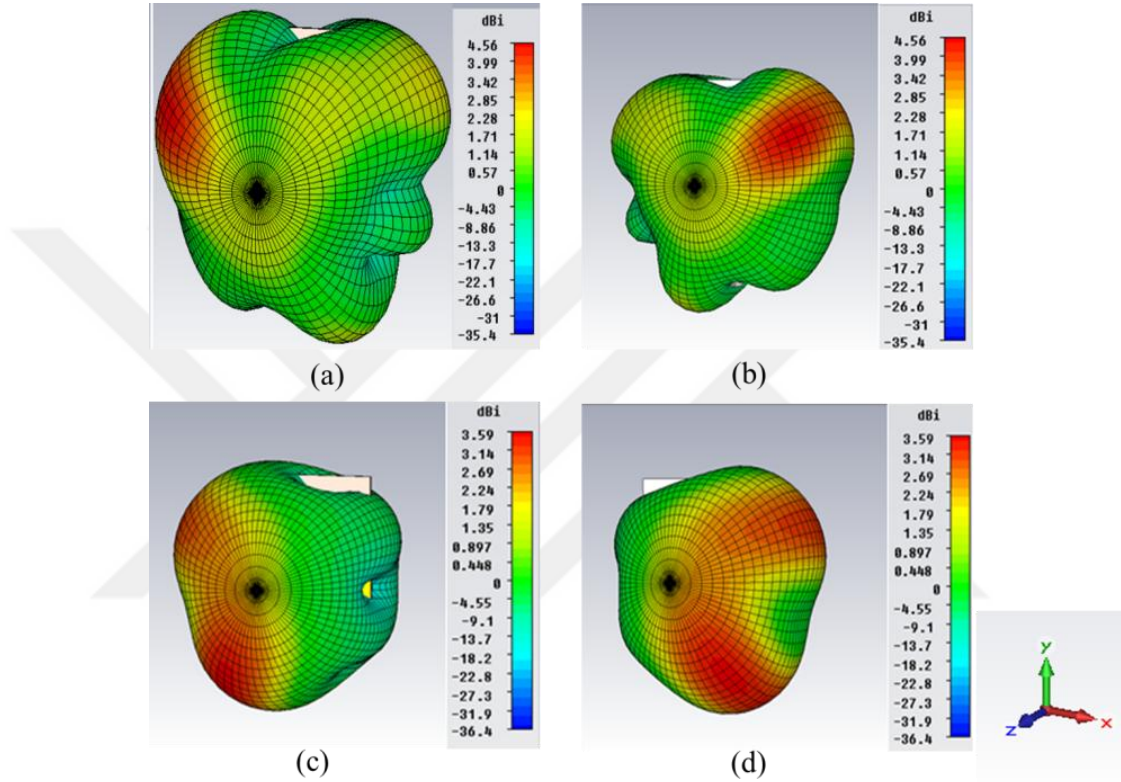


Figure 4.24. Reconfigurability of radiation patterns based on switch activation: a) 1001 mode at 9.75 GHz, b) 1100 mode at 9.75 GHz, c) 1001 mode at 6.84 GHz, d) 1100 mode at 6.84 GHz

4.1.5. Fabrication of the Proposed Antenna Model

The proposed antenna model is fabricated to ensure that the optimized antenna model parameters are valid for this work as depicted in Figure 4.25. The SMA connector is soldered to the antenna feeder. Additionally, the control unit set was fabricated and connected to the antenna design through DC cables, enabling the activation of the PIN diodes by biasing them with DC volts as shown in Figure 4.26. The control unit is powered by 5 volts DC, which is sufficient to bias this type of PIN diode. The S_{11} of the fabricated antenna model is tested on an R&S vertical network analyzer (VNA) type ZB40, allowing for the measuring of the antenna S_{11} parameter as illustrated in Figure 4.27.

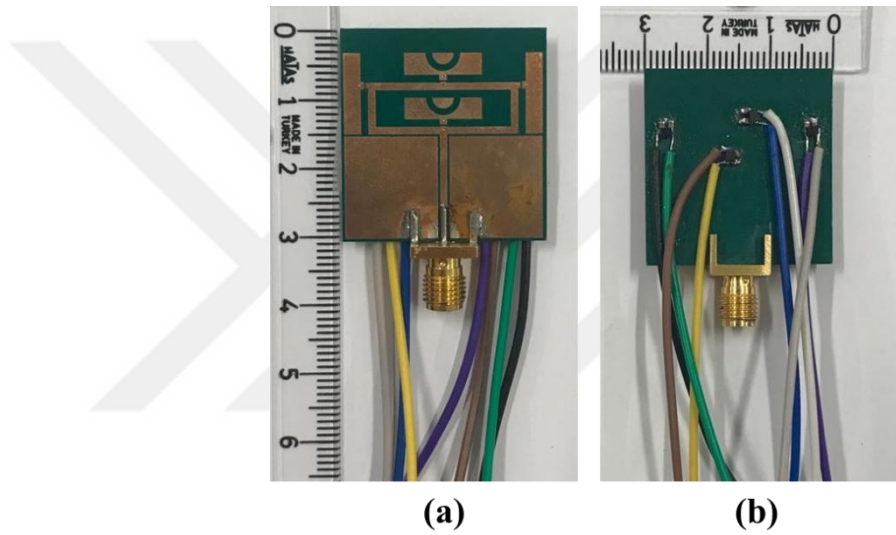


Figure 4.25. Fabricated antenna model, a) Frontal view, b) Rear view

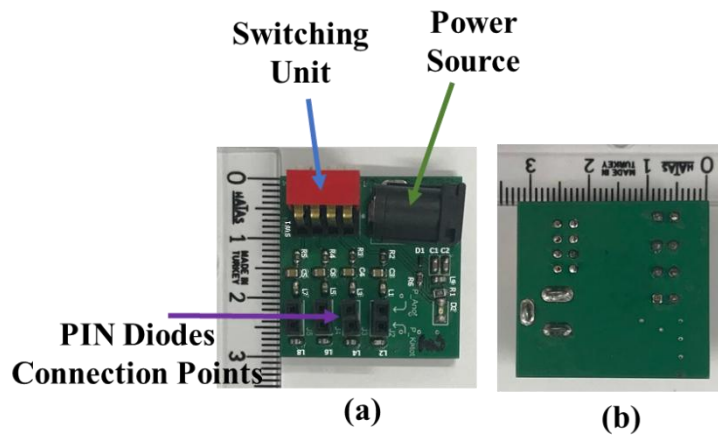


Figure 4.26. Fabricated control unit, a) Frontal view, b) Rear view

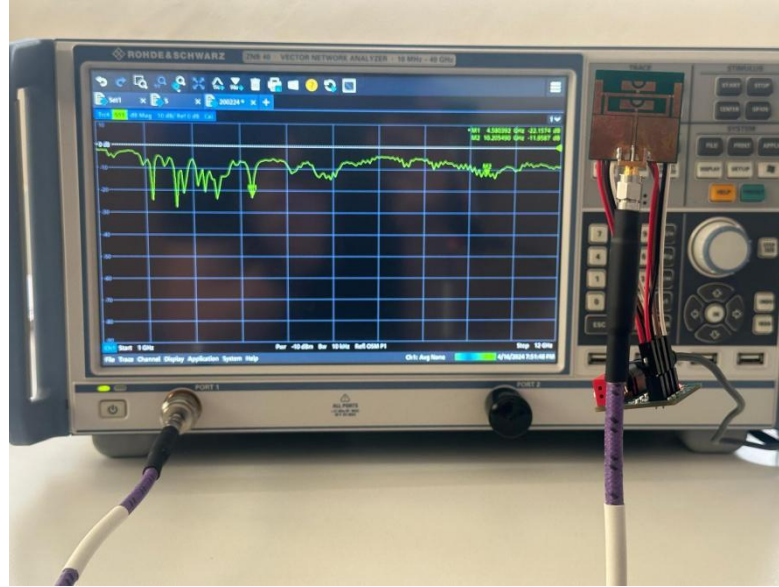


Figure 4.27. S_{11} parameter measurement using VNA

Figure 4.28 illustrates the S_{11} simulation outcomes for the proposed antenna as evaluated using CST, HFSS, and VNA. The S_{11} parameter for the antenna remains nearly identical in both simulation environments. In this set-up, the antenna functions across two frequency bands: the first band spans from 4.5 GHz to 5.2 GHz, corresponding to the C-band for satellite communication, featuring a bandwidth of 700 MHz and a resonance frequency of 5 GHz. Meanwhile, the second band operates between 9 GHz and 11 GHz, associated with the X-band for satellite communication, offering a bandwidth of 2 GHz and a resonance frequency of 10 GHz.

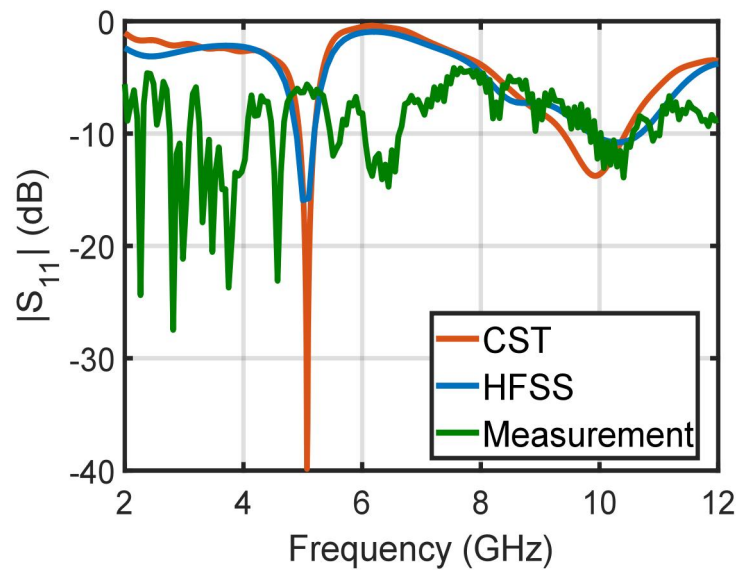


Figure 4.28. S_{11} parameter results of the simulated and fabricated antenna model

Additionally, Figure 4.25 displays the S_{11} measurement values of the first fabricated antenna model measured using a VNA as shown in Figure 4.27. This model exhibits noises and resonances lower than 4 GHz, and the operating bands of the antenna differ from those of the simulated antenna model. This discrepancy is attributed to the magnetic field emissions from the DC biasing cables connected to the PIN diodes mounted on the bottom layer of the antenna model. This issue is confirmed through the magnetic field probe connected to the spectrum network analyser, as illustrated in Figure 4.29. To address this problem, EMI absorber sheets are used to mitigate the impact of these emissions on the antenna properties, as depicted in Figure 4.30.

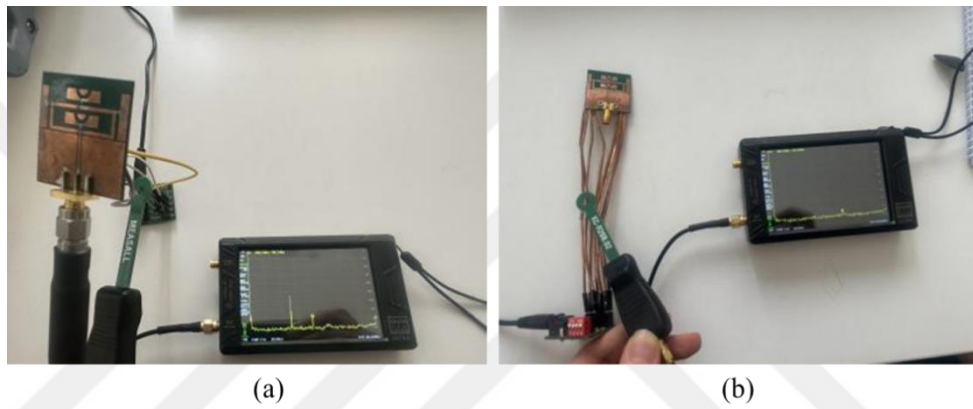


Figure 4.29. Checking the magnetic field emissions through a spectrum analyser, antenna model a) Without EMI, b) With EMI absorber

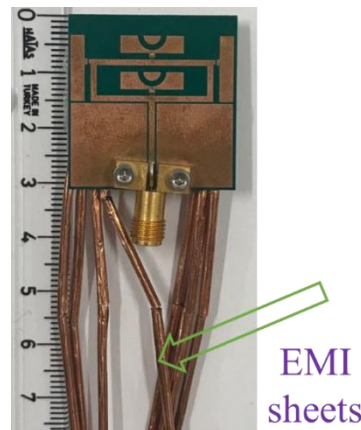


Figure 4.30. The fabricated antenna model with EMI isolation sheet

As a result, the fabricated antenna model begins to emit dual resonance frequencies similar to the simulated results. However, there are still noises below the 1.2 GHz threshold that need to be filtered out as measured in Figure 4.31, and compared with simulation is in Figure 4.32. The control unit is improved by adding a high-pass filter at the RF output to eliminate all noises lower than 1.2 GHz as illustrated in the circuit schematic in Figure 4.33. The final control unit with the filtering system is fabricated and assembled with the fabricated antenna model, which is isolated by electromagnetic interference sheets. The S_{11} parameter of the final antenna model is tested using the VNA as shown in Figure 4.34 that the unwanted signal bands that below 1.2 GHz were filtered already, and the measured values are compared with the simulation results as shown in Figure 4.35, which are revealing close similarity between the two of them, the antenna operates over dual bands one of them over the C-band with resonance frequency 5.1 GHz and bandwidth of 300 MHz, and another one over the X-band with resonance frequency 10 GHz and bandwidth of 1000 MHz.

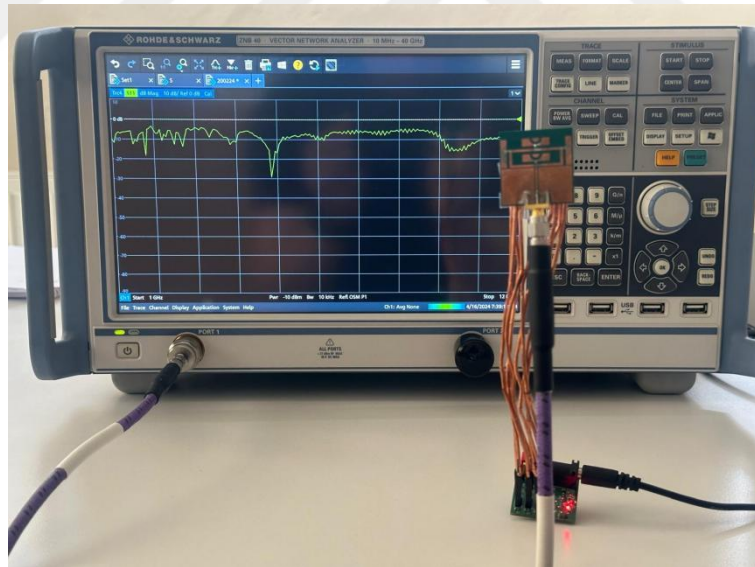


Figure 4.31. S_{11} measurement using VNA

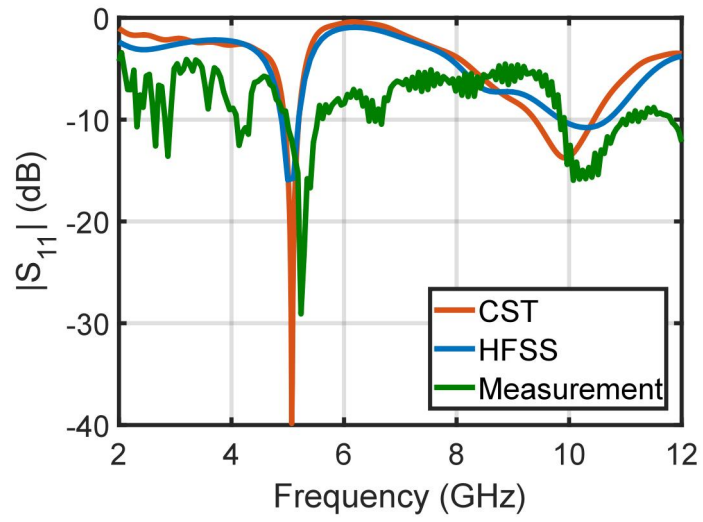


Figure 4.32. S_{11} parameter of the simulated model and fabricated antenna model that has EMI isolation sheets

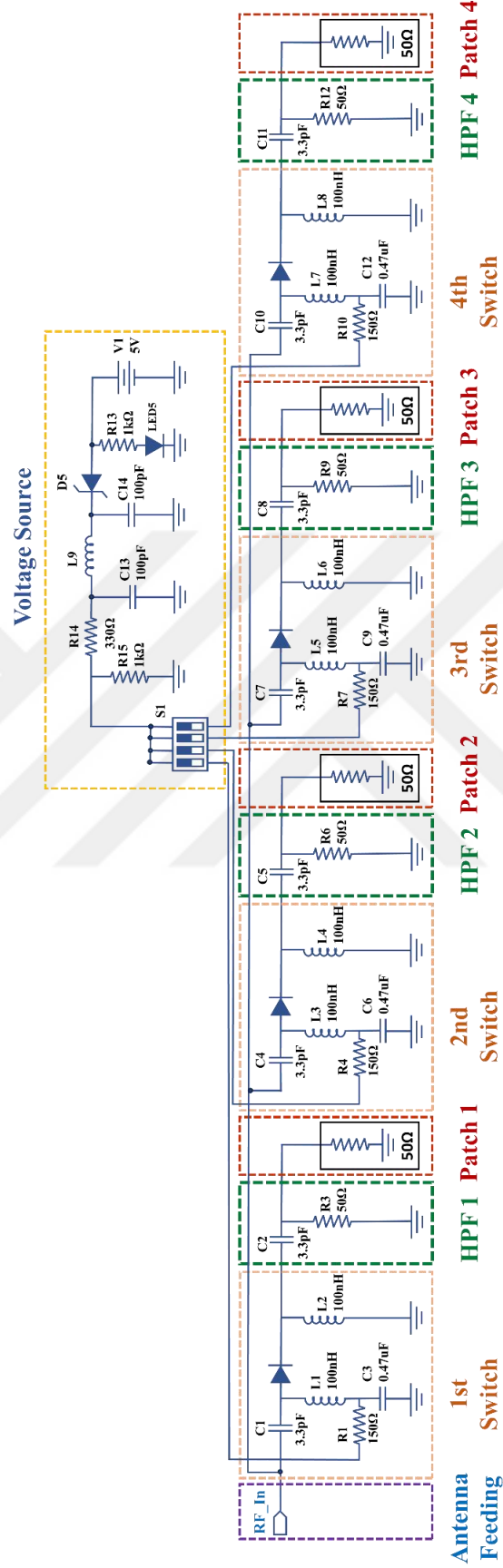


Figure 4.33. Final schematic diagram of the control unit with high pass filter

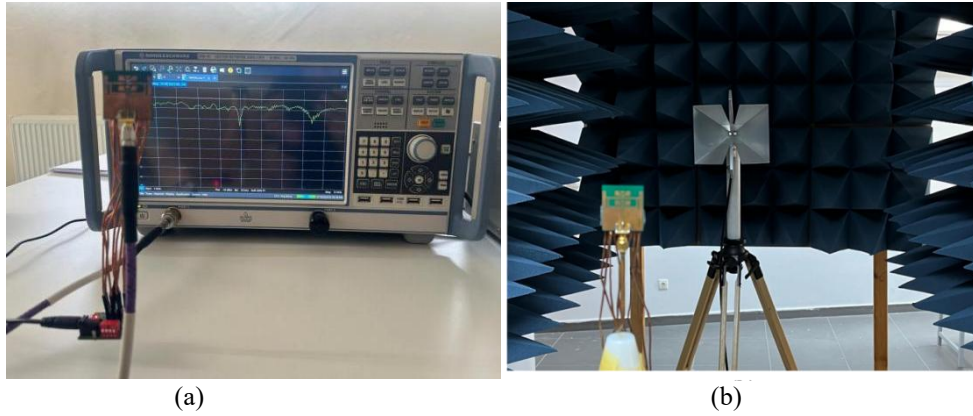


Figure 4.34.a) Vector Network Analyzer (VNA), b) Measurement of radiation patterns for the fabricated antenna.

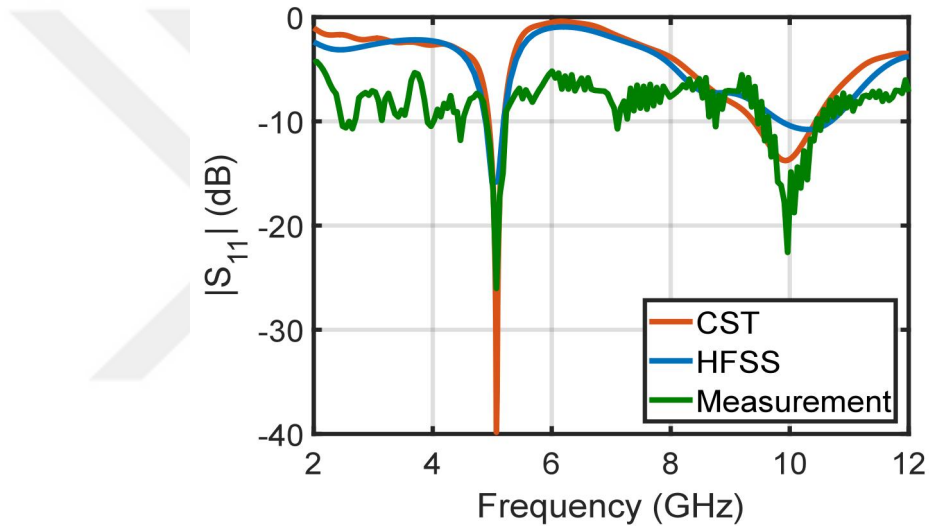


Figure 4.35. S_{11} results of recommended antenna model (with EMI sheets, and HPB filter)

For single-frequency operation in the C-band (5000–5300 MHz) and operation band in the X-band (9200–10400 MHz), the simulated and measured VSWR is below 1.5 as shown in Figure 4.36 over the operated dual bands in the C and X spectrum. As a result, the VSWR results indicate well-matched impedance; meanwhile, the simulated results are consistent with the measured results. The tuning frequency ratio (1.64:1) is achieved.

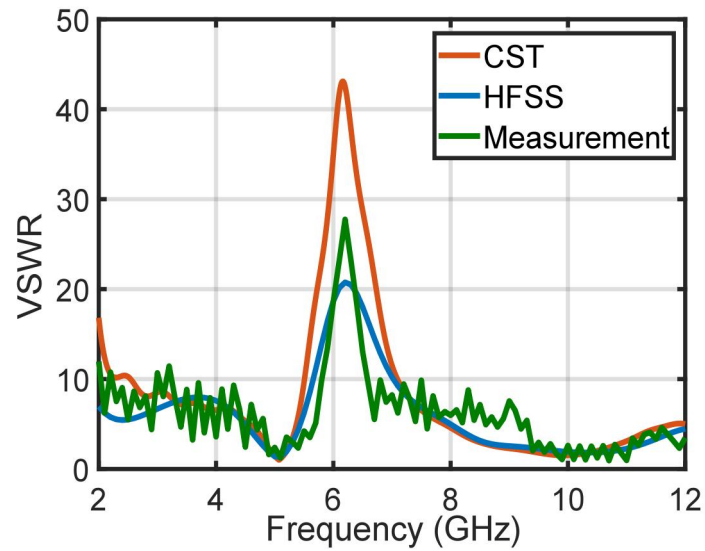


Figure 4.36. VSWR results of the recommended antenna design

4.1.6. Comparison with Related Works

The proposed antenna demonstrates strong performance when assessed against previous iterations. The design's compact form factor notably decreases space requirements when configuring multiple units in an array. Moreover, this design can support 14 different resonance frequency using the same antenna structural. Additionally, this single antenna configuration achieves a peak bandwidth, and gain of 1000 MHz, and 6.34 dBi respectively, as detailed in Table 4.5.

Table 4.5. Comparison with related works (simulation results)

Reference	Frequency (GHz)	Switching modes	Dimensions (mm ²)	Dielectric material	Peak Bandwidth (MHz)	Peak Gain (dBi)	Peak Efficiency (%)	Pattern Reconfiguration
(Zhang et al., 2022)	1.4, 2, 2.25, 3	2	124 × 124	Rogers 5880	100	4.23	70	No
(Mabrouk et al., 2022)	5.85, 5.48, 6.40, 6.56	2	99.6 × 99.6	7 layers FR-4	250	5.14	79	No
(Ghaffar et al., 2021)	1.65, 2.51	1	40 × 50	Rogers 6010	150	2.7	75	No
(Sreelakshmi et al., 2020)	1.65, 2.4, 2.51	2	24 × 19	Flexible poly-amide	280	3.96	83	No
(Ghaffar et al., 2020)	3.5, 6.78	2	26 × 22	Rogers TMMR-4	920	3.5	85	No
(Hussain et al., 2022)	5.2, 5.8	2	35 × 25	Polytetrafluoroethylene	470	3.3	78	No
(Saraswat And Harish, 2019)	2.25, 3.25	2	50 × 30	Transparent PETP film	410	3.5	91	No
(Awan et al., 2021)	3.5, 4.5	2	21 × 30	Rogers 5880	220	2.2	79	No
(Ullah et al., 2021)	1.55, 1.85, 2, 2.15	2	41 × 60	Rogers ro4003	450	3.9	86	No
(Rao et al., 2021)	2.1, 3.3, 3.5	2	37 × 35	FR-4	550	2.2	85	No
(Kumar et al., 2021)	14.9, 25.5	2	68.9 × 89.4	FR-4	950	3.3	78	No
(Sharma et al., 2020)	2.45, 4.72, 7.41	2	22 × 28	FR-4	600	4.25	81	No
Proposed	3.27, 3.45, 3.54, 4.16, 4.57, 4.99, 5.07, 5.55, 6.29, 7.3, 8.87, 9.78, 9.88, 9.93	16	30 × 28.4	Rogers 5880	1000	6.34 (one mode, 1010)	98 (one mode, 0010)	Two modes supported

4.2. Antenna Design for 6G Satellite Frequency Bands

This section introduces an innovative MIMO antenna design that is adaptable for frequency reconfiguration, specifically targeting 6G satellite communications in the D-band and THz band. The antenna boasts a compact quad-port structure, measuring $2.951 \times 2.95 \times 0.127 \text{ mm}^3$, and utilizes Rogers RT5880 substrate known for its dielectric constant of 2.2. Integrated within the antenna is a PIN diode that enables it to toggle across six different frequency bands, extending from 120 GHz to 250 GHz. The bandwidth offered by this design reaches up to 27 GHz. This antenna configuration provides a peak gain of 8.27 dBi and an efficiency of 92%. The design of this MIMO antenna has been optimized for superb performance, achieving less than -45 dB inter port isolation, nearly zero correlation coefficients, and a diversity gain of 10 dB. This makes the compact and versatile MIMO antenna an excellent choice for broad frequency range applications, offering high gain and efficiency, which are vital for the demands of 6G communications in the D-band.

4.2.1. Antenna Geometry Design and Analysis

Designing a microstrip antenna with a compact form factor, wide bandwidth, high gain, and low return loss presents a significant challenge. In the proposed antenna design, Rogers material has been selected as the substrate layer due to its ability to optimize the single element antenna's physical dimensions, mechanical strength, and electromagnetic performance as shown in Figure 4.37. This results in a compact antenna with dimensions of $1.07 \times 1.5 \times 0.127 \text{ mm}^3$. The material properties of Rogers substrate play a crucial role in shaping the antenna's radiation behaviour, frequency response, and electromagnetic interactions. To improve the antenna's gain and efficiency, the patch is designed in a rectangular configuration with U-shaped slots etched into the patches. The 2×2 MIMO antenna design is realized by arranging four individual patches with appropriate spacing (wavelength divided by 2), and a quad-port feeding mechanism is used. The MIMO antenna's ground plane is critical for controlling radiation and reducing electromagnetic reflections from the antenna's underside. This is achieved by placing four copper ground sections, each 0.035 mm thick, on the bottom of the substrate, directly beneath each antenna patch. The 2D and 3D geometry of the antenna design, shown in Figure 4.38 and detailed in Table 4.6, provides a clear representation of the antenna's dimensions. For modelling

and simulation, CST and HFSS Microwave Studio software are utilized to create and analyse the antenna geometry.

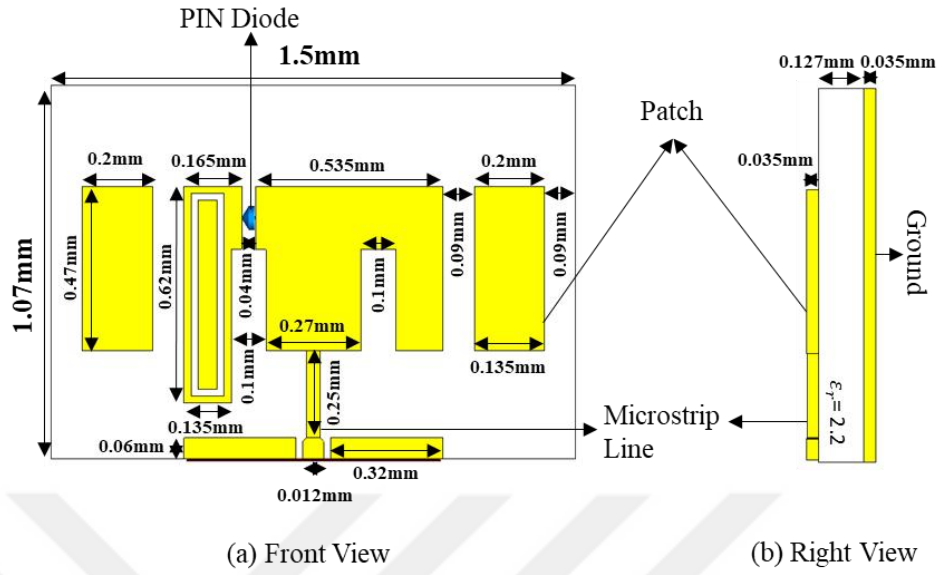


Figure 4.37. Single element antenna geometry, a) 2D front view, b) 2D side view

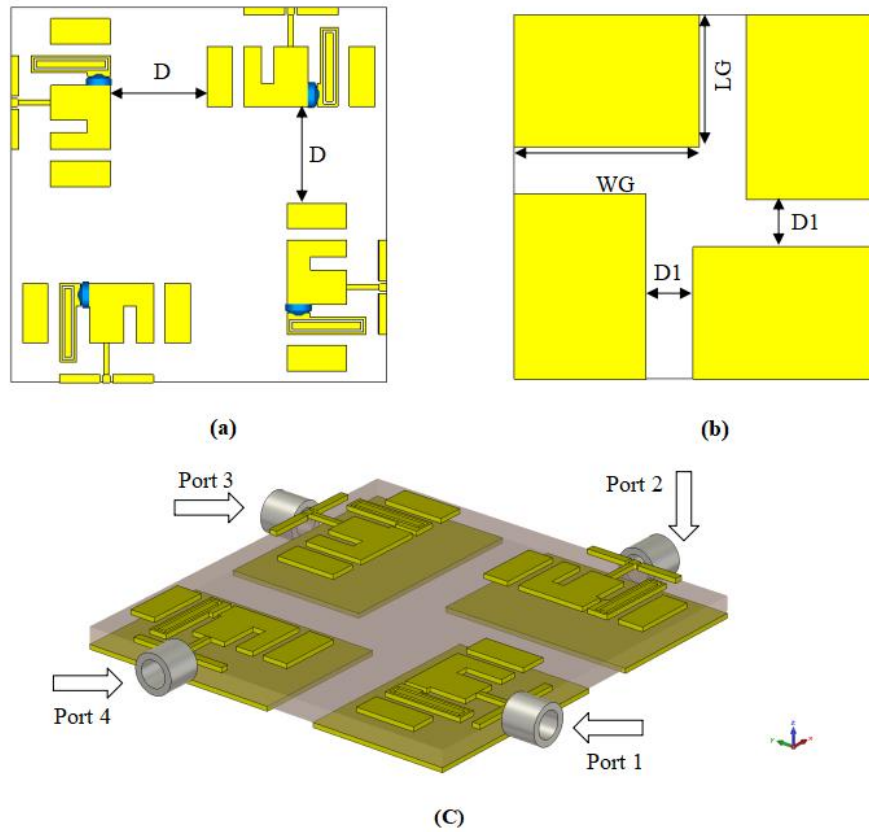


Figure 4.38. Proposed MIMO antenna geometry, a) 2D front view, b) 2D back view, and c) 3D design of the 2 x 2 MIMO antenna model.

Table 4.6. Proposed MIMO antenna geometry dimensions

Parameter	Dimension (mm)	Parameter	Dimension (mm)
D	0.761	D1	0.381
LG	1.07	WG	1.5

4.2.2. Simulation Results of Antenna Model

The goals for 6G satellite systems are to achieve high-speed transmission, expansive bandwidth, low latency, and enhanced performance, as noted in recent studies (Jayanth et al., 2023; Wikström et al., 2020). Displayed in Figure 4.39, the S_{11} parameter for this antenna model is analysed using both HFSS and CST simulations, illustrating its adaptability. This antenna functions at three resonance frequencies within the D-band as 135 GHz, 169 GHz, and 196 GHz. At these specific frequencies, the S_{11} parameter maintains a consistent level below -10 dB, with bandwidths reaching 5 GHz, 20 GHz, and 15 GHz, respectively. Moreover, this MIMO antenna is noted for its robust port isolation at each frequency, consistently achieving less than -40 dB as detailed in Figure 4.40 and documented in Table 4.7.

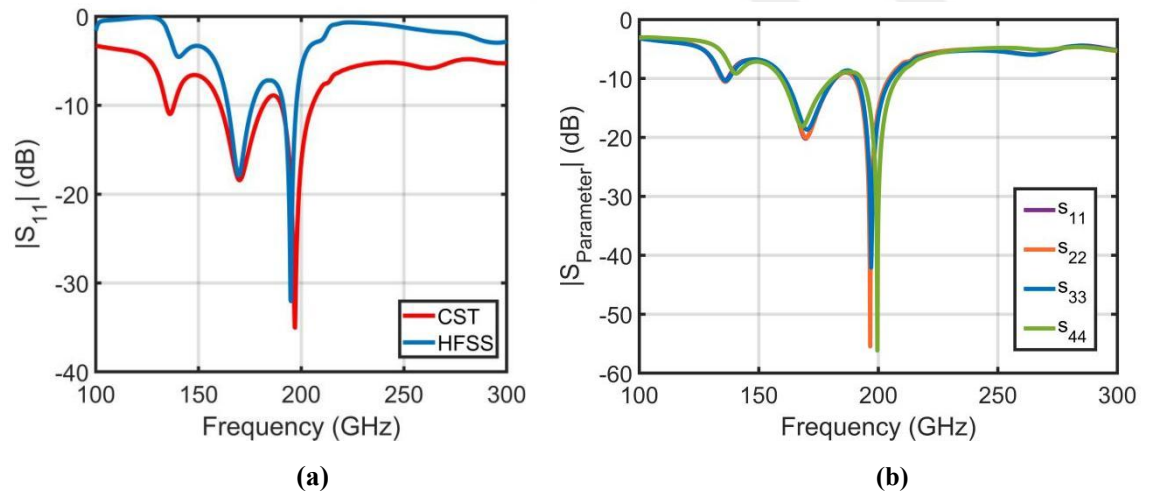


Figure 4.39. Simulated S_{11} parameter results, a) Comparison CST with HFSS, b) Different antenna ports

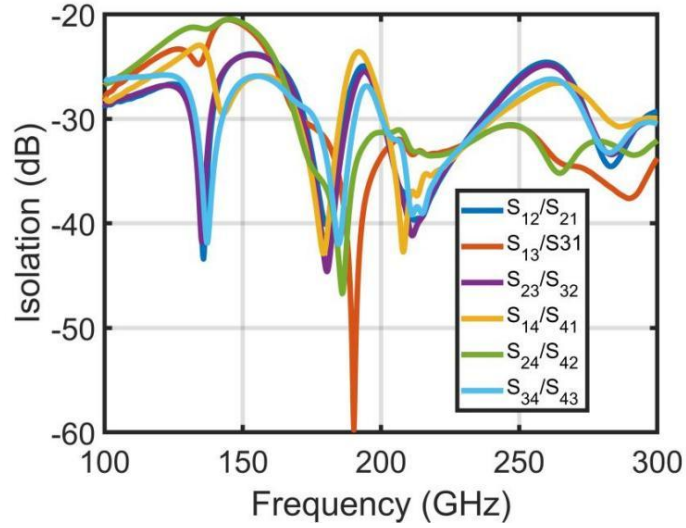


Figure 4.40. Isolation parameters between antenna ports

Table 4.7. Comparison between resonance frequencies isolation

S-Parameters	S-Parameter (dB)		
	135 GHz	169 GHz	196 GHz
S_{12}/S_{21}	-39.495	-27.329	-25.663
S_{13}/S_{31}	-24.619	-29.508	-35.988
S_{14}/S_{41}	-23.011	-29.202	-25.165
S_{23}/S_{32}	-41.457	-27.871	-26.009
S_{24}/S_{42}	-21.368	-29.805	-31.774
S_{34}/S_{43}	-34.729	-28.359	-27.099

Figure 4.41 demonstrates the directional radiation patterns of the antenna designed for frequencies of 135 GHz, 169 GHz, and 196 GHz. The antenna shows directional radiation along the propagation paths in both the E-plane and H-plane, with peak gains reaching 7.18 dBi, 8.5 dBi, and 7.97 dBi at the respective frequencies. Furthermore, the efficiency at these frequencies stands at 85%, 92%, and 89%, respectively. In MIMO antenna designs, the envelope correlation coefficient (ECC) is critical for evaluating how similarly the signal envelopes of different antenna elements behave. Achieving a low ECC is advantageous as it ensures more independence among the antenna elements, minimizing undesirable correlations. The ECC for this MIMO antenna is calculated using methodologies outlined in recent research (Jayanth et al., 2023; Wikström et al., 2020), and the

correlation coefficients (CCs) are established from the S-parameters and normalized equivalent resistances, as outlined in Equations 4.1 - 4.3 (Malviya et al., 2020).

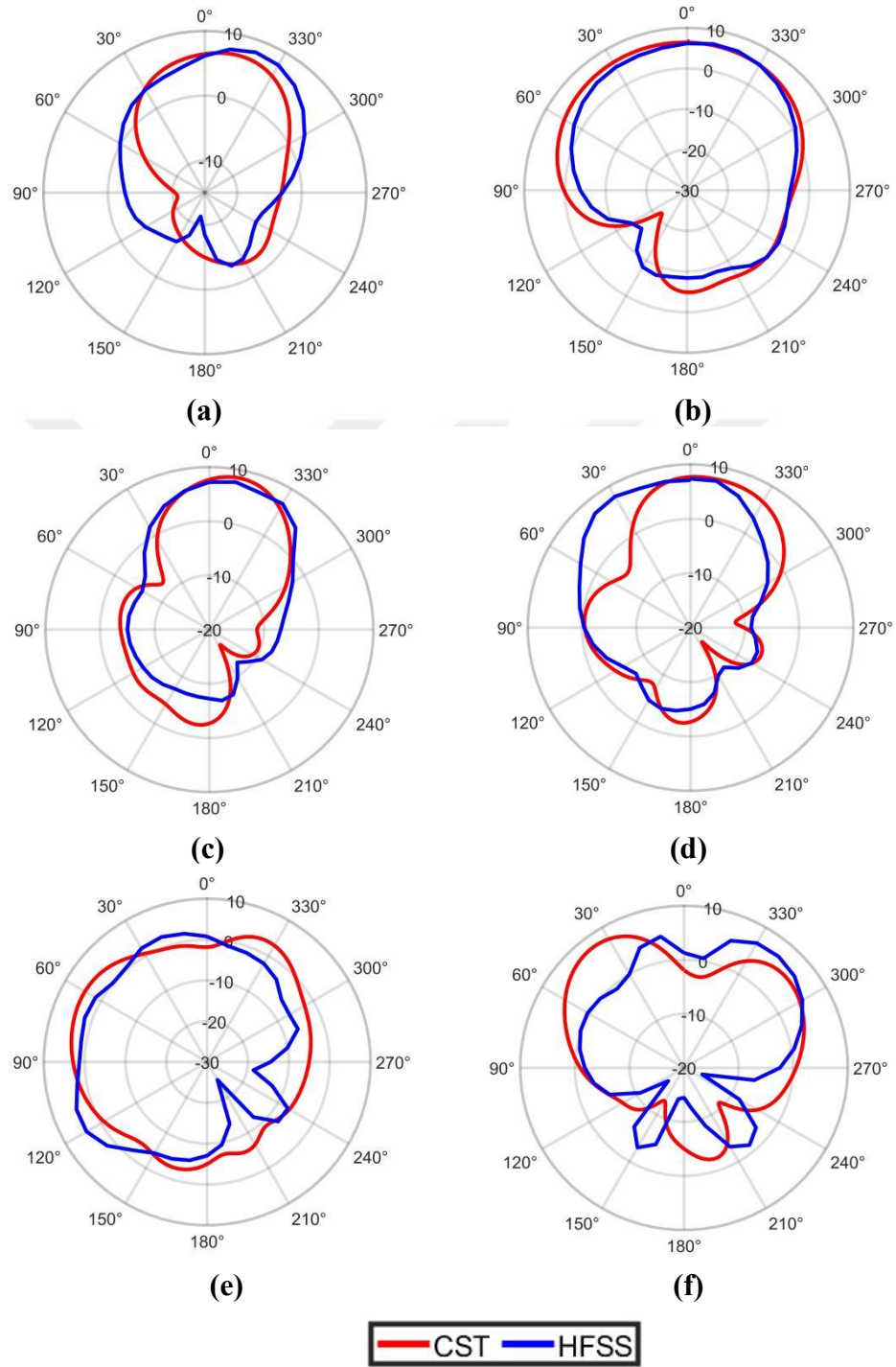


Figure 4.41. The polar form radiation pattern, a) E-Plane at 135 GHz, b) H-Plane at 135 GHz, c) E-Plane at 169 GHz, d) H-Plane at 169 GHz, e) E-Plane at 196 GHz, and f) H-Plane at 196 GHz.

$$\rho_e(i, j) = \rho_s(i, j) = \frac{|\sum_{m=1}^M S_{i,m}^* S_{m,j}|^2}{\prod_{k=i,j} [1 - \sum_{m=1}^M S_{k,m}^* S_{m,k}]} \quad (4.1)$$

$$\rho_e(i, j) = |\rho_r(i, j)|^2 = |r_{i,j}|^2 = \frac{|R_e(Z_{i,j})|^2}{|R_e(Z_{i,i})|} \quad (4.2)$$

$$\rho_e(1,2) = \frac{|S_{11}^* S_{12} + S_{12}^* S_{22} + S_{13}^* S_{32} + S_{14}^* S_{42}|}{(1 - (S_{11}^* S_{11} + S_{12}^* S_{21} + S_{13}^* S_{31} + S_{14}^* S_{41})) (1 - (S_{21}^* S_{12} + S_{22}^* S_{22} + S_{23}^* S_{32} + S_{24}^* S_{42}))} \quad (4.3)$$

The interaction between two antenna ports is measured using the correlation coefficient $\epsilon(i, j)$, calculated as a ratio of the ports, the number of elements (K), and the impedance (Z). The outcomes for these coefficients, illustrated in Figure 4.42(a), show $\epsilon(i, j)$ nearing zero, indicating minimal S-parameter and normalized mutual resistance correlation, with values as low as 0.0009. As detailed in Table 4.8, these simulation results are consistently low, with $\epsilon(i, j)$ staying under 0.0001 for the S-parameters at the designated resonance frequencies. Table 4.9 details the diversity gain simulation results for the MIMO antenna at resonance frequencies of 135 GHz, 169 GHz, and 196 GHz, based on the S-parameters. Adjusting by a scaling factor of 0.99 enhances the accuracy of the results, showing in Figure 4.42(b) a maximum diversity gain of 10 achieved at a 1% probability level through selection combining. An approximate expression for correlation efficiency has been calculated, demonstrating the effectiveness of the antenna set-up.

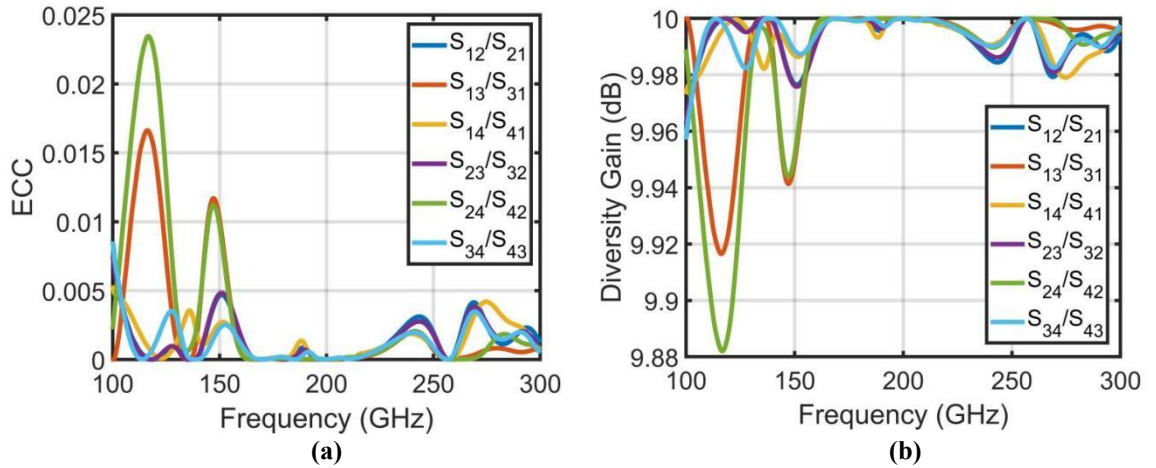


Figure 4.42. MIMO proprieties of antenna model, a) ECC, b) Diversity gain

Table 4.8. ECC at the proposed resonance frequencies

S-Parameters	Correlation Coefficients (dB)		
	135 GHz	169 GHz	196 GHz
S ₁₂ / S ₂₁	2.15e-5	2.42e-6	4.40e-6
S ₁₃ / S ₃₁	5.01e-6	1.29e-5	2.35e-7
S ₁₄ / S ₄₁	3.40e-3	1.02e-5	9.77e-5
S ₂₃ / S ₃₂	4.43e-6	1.06e-6	7.98e-6
S ₂₄ / S ₄₂	6.30e-4	4.09e-5	2.21e-5
S ₃₄ / S ₄₃	2.65e-4	1.12e-5	8.09e-5

Table 4.9. DG at the proposed resonance frequencies

S-Parameters	Diversity Gain (dB)		
	135 GHz	169 GHz	196 GHz
S ₁₂ /S ₂₁	9.9998741	9.9999879	9.999978
S ₁₃ /S ₃₁	9.999975	9.9999353	9.9999988
S ₁₄ /S ₄₁	9.9828795	9.999949	9.9995114
S ₂₃ /S ₃₂	9.9999778	9.9999947	9.9999601
S ₂₄ /S ₄₂	9.9968502	9.9997956	9.9998896
S ₃₄ /S ₄₃	9.9986712	9.9999439	9.9995954

4.2.3. Analysis of Frequency Reconfiguration Mode

Satellite communication utilizes Earth observation satellites to enable data transmission across various regions worldwide through telecommunication services. It is essential to the global communication infrastructure, facilitating a substantial share of the world's voice, data, and image transfers. Nonetheless, satellite signals can be susceptible to jamming, which can occur by directing a powerful transmission at the satellite or employing frequency-hopping techniques on the transceiver sides (Jayanth et al., 2023; Wang et al., 2022). To mitigate this vulnerability, the current study integrates frequency reconfiguration into the antenna design, enabling it to adjust its operating frequency bands in accordance with the reconfigured transceiver channels. This frequency reconfiguration is accomplished by incorporating four PIN diodes (model: MA4AGBL912) between the antenna patches and their corresponding circular slotted rectangular plates, represented as lumped elements (RLC circuits) in both HFSS and CST simulations, CST model illustrated in Figure 4.43. When the PIN diodes are in an inactive state, the antenna functions

within the frequency bands specified in the second section, based on the initial antenna geometry design. However, upon activation of the PIN diodes, the operating frequency bands shift to 125 GHz, a wide-band range from 182 GHz to 205 GHz, and 222 GHz, exhibiting S_{11} parameter values lower than -10 dB and bandwidths of 5 GHz, 23 GHz, and 6 GHz, respectively, as shown in Figure 4.44.

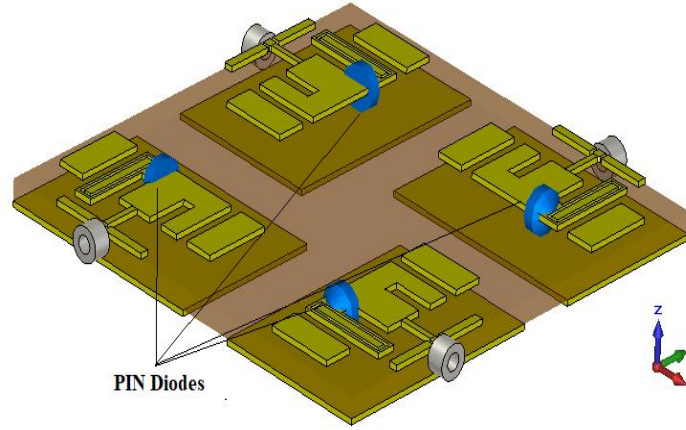


Figure 4.43. Proposed reconfigurable MIMO antenna design

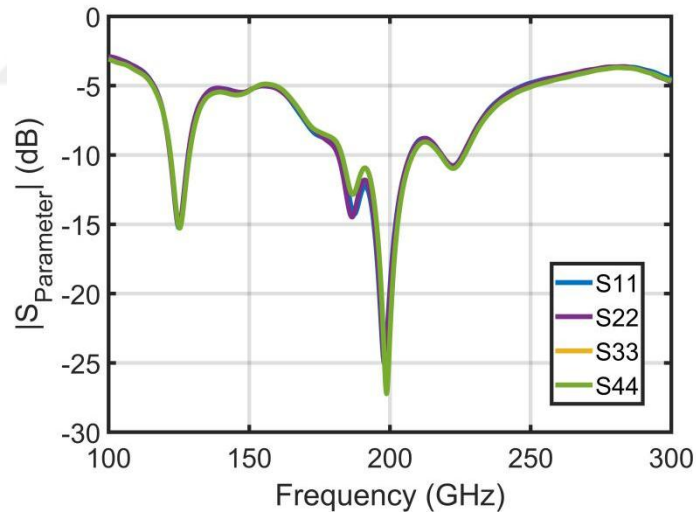


Figure 4.44. Simulated S_{11} parameter of the reconfigured MIMO antenna with PIN diodes at active mode

Figure 4.45 reveals that with the PIN diodes deactivated, the surface current mainly resides on the right side of the patch antenna, influencing resonance at frequencies of 135 GHz, 169 GHz, and 196 GHz. A PIN diode activation prompts a redistribution of this surface current to the left circular slotted copper plate at the same frequencies. This redistribution suggests that after the diode is activated, the

current starts to flow predominantly through the left side of the patch antenna. With all PIN diodes operational, the MIMO antenna's polar radiation patterns are adjusted resonance frequencies of 125 GHz, 187 GHz, and 198 GHz. Figure 4.46 displays the radiation patterns at these frequencies, which show semi-directional radiation characteristics across both the E-plane and H-plane. The gains and efficiencies related to these radiation patterns are detailed in Table 4.10.

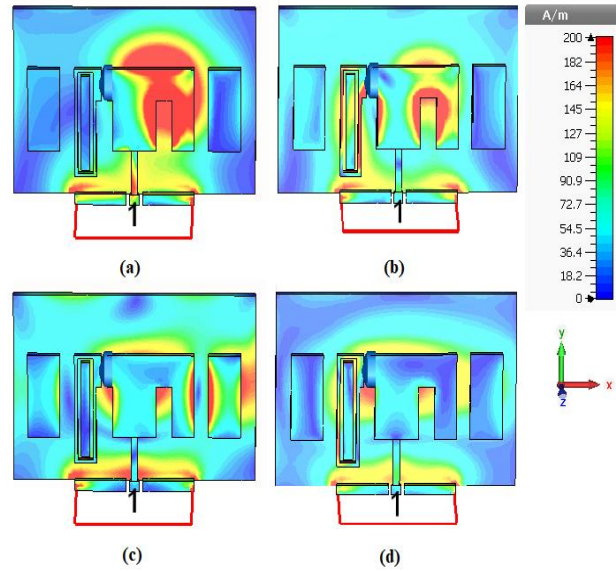


Figure 4.45. Surface current of the reconfigured MIMO antenna, a) PIN diode inactive mode at 125 GHz, b) PIN diode active mode at 125 GHz, c) PIN diode inactive mode at 187 GHz, d) PIN diode active mode at 187 GHz.

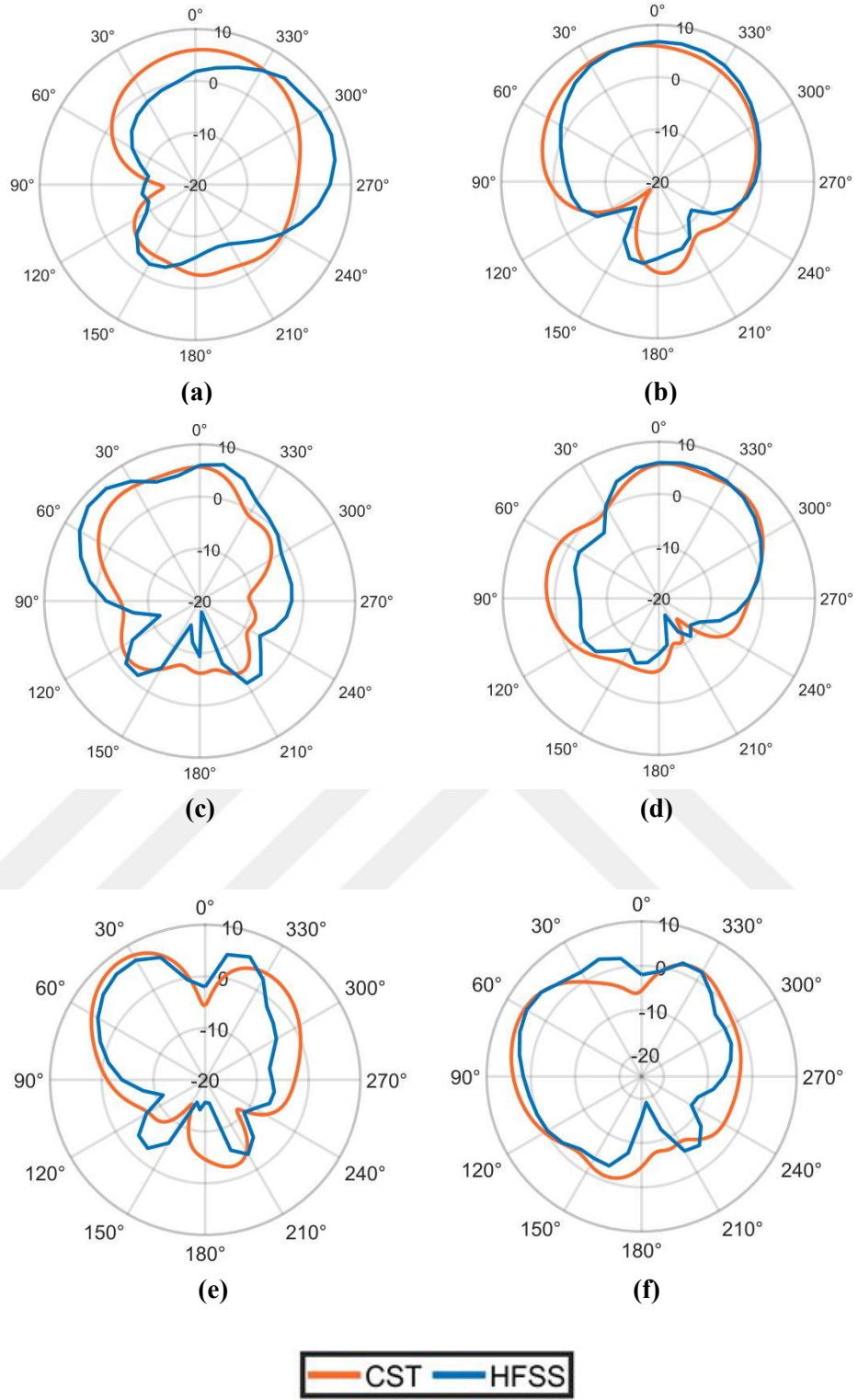


Figure 4.46. Polar form radiation pattern, a) E-Plane at 125 GHz , b) H-Plane at 125 GHz, c) E-Plane at 187 GHz,d) H-Plane at 187 GHz, e) E-Plane at 198 GHz,f) H-Plane at 198 GHz

Table 4.10. Gains and total efficiencies according proposed resonance frequencies

Frequency (GHz)	Gain (dBi)	Efficiency (%)
125	6.56	86
187	6.09	89
198	8.18	90

4.2.4. Comparison with Related Works

The proposed reconfigurable MIMO antenna demonstrates strong performance in terms of gain and total radiation efficiency, as shown in Table 4.11. When compared to prior antenna designs, the current model stands out by functioning as a MIMO antenna with the added capability of reconfiguring its frequency bands. It operates across six different bands, achieving the highest bandwidth of 20 GHz, a maximum gain of 8.25 dBi, and a total efficiency of 92% at the proposed resonance frequencies. This highlights the superior performance of the proposed design over previous works.

Table 4.11. Comparison with previous works (simulation results)

References	Frequency	Key highlights
(Altaf et al., 2023)	(110–130 GHz) (130–158.6 GHz) (154–170 GHz)	Elliptically tapered slot antennas based on Substrate Integrated Wave guide (SIW) technology for a 2x2 MIMO configuration have been designed. These antennas attain ECC below 0.5, demonstrate an efficiency of 80%, and deliver a total gain of 6.15 dBi.
(Jalil et al., 2022)	(330–350 GHz)	A 2x2 phased array antenna has been engineered to achieve a gain of 4 dBi and an operational efficiency of 40%.
(Kucharski et al., 2019)	(110–170 GHz)	The Planar antenna, designed for Integrated Radar Sensors, operates at 165 GHz and features a high-efficiency, high-gain profile. It achieves a maximum gain of 1 dBi and an efficiency of 45%.
(Maktoomi et al., 2022)	(90–128 GHz)	A Sub-Terahertz wide-band stacked-patch antenna, constructed on a 4-layer Flexible Printed Circuit tailored for 6G applications, showcases a peak gain of 7.95 dBi. This sophisticated design also achieves an impressive efficiency of 89%.
(Yi et al., 2021)	(220–320 GHz)	An ultra-broadband frequency modulated continuous wave radar antenna utilizing a frequency-comb architecture achieves a peak gain of 7 dBi and an efficiency of 25%.
Proposed design	(133–138 GHz) (159–182 GHz) (190–204 GHz) (121–128 GHz) (182–192 GHz) (192–208 GHz)	A frequency reconfigurable MIMO antenna designed for 6G satellite applications exhibits an ECC near zero. It achieves a peak gain of 8.49 dBi and maintains an efficiency of 92%.

5. RESULTS AND SUGGESTIONS

5.1. Results

This thesis has demonstrated the development of two innovative frequency-reconfigurable antenna designs tailored for satellite communication systems, addressing critical challenges such as jamming, interference, and operational flexibility. These antennas offer a physical solution to the frequency-hopping technique, a widely used method for combating jamming by dynamically altering the operating frequency of communication systems. Unlike purely software-based approaches, the proposed designs achieve frequency agility directly through hardware reconfiguration, enhancing system reliability and security while reducing complexity in implementation. The integration of frequency reconfigurability not only enables these antennas to dynamically adjust their operating frequencies to mitigate jamming but also enhances their adaptability to varying communication requirements. By modifying radiation patterns and transitioning to configurations like end-fire, the antennas effectively obscure the communication link, making it difficult for jammers to disrupt the signal, thereby ensuring secure and reliable data transmission in satellite networks. The designs presented in this work showcase significant advancements in reconfigurable antenna technology. The first design, operating in the S/C/X bands, and the second, designed for D-band 6G satellite systems, highlight the versatility of frequency-reconfigurable antennas. These antennas provide compact, cost-effective, and efficient solutions for satellite communication, particularly where space and weight constraints are critical. Furthermore, their integration of fast-switching RF PIN diodes enables seamless transitions across multiple frequency bands without the need for additional hardware, reducing system complexity. Beyond satellite communication, the compact size, high efficiency, and dynamic frequency adjustment capabilities of these antennas make them ideal for mobile systems where space and cost are limited. This makes them a promising solution for applications in hand-held devices, drones, and other portable communication platforms. The demonstrated performance, including high gain, excellent efficiency, and robust inter-port isolation, underscores their potential to become key components in next-generation communication systems.

The initial antenna model is engineered for fully controlled frequency reconfiguration, maintaining high levels of performance across diverse frequency

spectrum. This system ensures sustained effectiveness, utilizing Rogers material for the substrate with a compact footprint of $28.4 \times 30 \times 0.508 \text{ mm}^3$ and a relative permittivity of 2.2. The design strategically employs top, left, centre, and right patches with coplanar wave-guide patches, enhancing the material integration and connectivity. Activation through four separate PIN diodes establishes robust electrical connections between these patches and the feed line. This set-up enhances electrical flow and supports modifications in the antenna's physical dimensions, which facilitates frequency reconfiguration. The antenna's design allows it to handle 16 different operational modes, covering a range of resonance frequencies from 3.27 GHz to 9.93 GHz, across S, C, and X bands for satellite communication. This configuration results in unidirectional radiation patterns, yet it allows for directional flexibility to either end of the antenna as needed. Remarkably, the antenna peaks at a gain of 6.34 dBi (through one operation mode only) at 8.61 GHz and achieves an efficiency of 98% (through one operation mode only) at 8.87 GHz. These results confirm the model's expansive bandwidth and robust performance, underscoring its enhanced capacity for broadening operational spectra compared to prior models. The antenna is celebrated for its high gain, superior impedance matching, and high efficiency, marking it as exceptionally suitable for satellite communication applications.

The second antenna design is an innovative quad-port MIMO antenna model specifically engineered for operation within the 6G satellite frequency bands, incorporating frequency reconfiguration capabilities. The selection of Rogers RT5880 materials for the substrate layer is based on their low tangent loss, which enhances efficiency. This design features a single PIN diode integrated into the patch layer, providing two operational modes. In its inactive state, the diode permits operation at three resonance frequencies: 135 GHz, 169 GHz, and 196 GHz. When activated, the resonance frequencies shift to 125 GHz, 187 GHz, and 198 GHz. This antenna model showcases a bandwidth of 20 GHz centred around a resonance frequency of 169 GHz, with a maximum gain of 8.49 dBi and an efficiency of 92%. The radiation patterns of the antenna are predominantly directional, and the MIMO ports achieve nearly -40 dB isolation, with coherence coefficients approaching zero. Furthermore, the diversity gain reaches 10, indicating strong performance in comparison to prior works in the field of 6G satellite communication systems.

Overall, this thesis establishes frequency-reconfigurable antennas as a cornerstone for addressing modern communication challenges, offering a secure, flexible, and scalable approach to ensuring reliable connectivity in both satellite and mobile systems. By providing a physical implementation of the frequency-hopping technique, these designs represent a significant step forward in safeguarding communication networks from jamming and interference while paving the way for further innovations in reconfigurable antenna technologies.

5.2. Suggestions

The presented antenna designs could be further enhanced through several advanced strategies that combine adaptive technologies and material innovations. Integrating adaptive beamforming techniques would allow real-time adjustments to the radiation pattern, bolstering performance in complex signal environments while mitigating jamming risks. Additionally, exploring alternative substrate materials, such as liquid crystal polymers or low-loss ceramics, could improve thermal stability and efficiency, crucial for satellite applications where material reliability is paramount. Extending the designs to support multi-mode and multi-band operation would increase versatility, enabling a single antenna to handle diverse satellite communication needs and reducing system complexity. Lastly, hybrid reconfiguration techniques that blend electronic, mechanical, or optical switching could enhance operational flexibility, offering faster response times and supporting a wider range of reconfiguration modes to adapt to dynamic satellite communication environments.

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CURRICULUM VITAE

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Publications:

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