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Theme

A Comprehensive Investigation into Patch Antenna Array Design for 5G Networks

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Abstract

This thesis presents a comprehensive investigation into patch antenna array design for 5G networks, with a focus on millimeter-wave (mmWave) frequencies. Beginning with an exploration of the evolution of mobile communication and an in-depth examination of antenna theory, the thesis transitions to practical implementation in chapter 3, utilizing High-Frequency Structure Simulator (HFSS) for design and optimization. Through meticulous analysis and simulation, various design methodologies, optimization techniques, and simulation tools are explored to develop efficient and high-performing antenna arrays. Recognizing the need for high gain (over 12 dBi) in 5G systems. Two-element and four-element antenna array designs are presented, successfully achieving the target gain of over 12 dBi at both resonant frequencies (36 GHz and 38 GHz). The culmination of this research contributes to the advancement of antenna technology, providing valuable insights and practical guidance for researchers, engineers, and practitioners seeking to harness the full potential of 5G communications in the mmWave era.

Key words: 5G, Patch antenna, Array antenna, HFSS, mmWaves.

Résumé

Cette dissertation présente une étude approfondie sur la conception d'antenne en réseau pour les réseaux 5G, en mettant l'accent sur les fréquences millimétriques. En commençant par une exploration de l'évolution de la communication mobile et un examen approfondi de la théorie des antennes, la thèse passe à la mise en œuvre pratique au chapitre 3, en utilisant le simulateur de structure haute fréquence (HFSS) pour la conception et l'optimisation. À travers une analyse et une simulation minutieuses, diverses méthodologies de conception, techniques d'optimisation et outils de simulation sont explorés pour développer des réseaux d'antennes efficaces et performants. Reconnaissant la nécessité d'un gain élevé (supérieur à 12 dBi) dans les systèmes 5G, des conceptions de réseaux d'antennes à deux éléments et à quatre éléments sont présentées, atteignant avec succès le gain cible de plus de 12 dBi à toutes les fréquences de résonance (36 GHz and 38 GHz). L'aboutissement de cette recherche contribue à l'avancement de la technologie des antennes, fournissant des informations précieuses et des conseils pratiques aux chercheurs, ingénieurs et praticiens cherchant à exploiter pleinement le potentiel des communications 5G dans le domaine des ondes millimétriques.

Mots-clés: 5G, Antenne patch, Réseau d’antenne, HFSS, Ondes millimétriques.

ملخص

تقدم هذه الأطروحة تحقيقًا شاملاً في تصميم مصفوفة هوائيات الرقعة لشبكات الجيل الخامس، مع التركيز على ترددات الموجات المليمترية .(mmWave) تبدأ الأطروحة باستكشاف تطور الاتصالات المتنقلة وفحص متعمق لنظرية الهوائي، ثم تنتقل إلى التطبيق العملي في الفصل الثالث، باستخدام برنامج محاكي الهيكل عالي التردد (HFSS) للتصميم والتحسين. من خلال التحليل الدقيق والمحاكاة، يتم استكشاف مختلف منهجيات التصميم وتقنيات التحسين وأدوات المحاكاة لتطوير مصفوفات هوائيات ذات كفاءة عالية وأداء متميز. بالاعتراف بالحاجة إلى كسب عالٍ (أكثر من 12 ديسيبل) في أنظمة الجيل الخامس، يتم تقديم تصميمات لمصفوفة هوائيات مكونة من عنصرين وأربعة عناصر، حيث تحقق بنجاح الهدف المنشود لكسب أكثر من 12 ديسيبل عند كلا الترددين الرنينيين (36 جيجاهرتز و38 جيجاهرتز). تساهم هذه الدراسة في تقدم تكنولوجيا الهوائيات، وتقدم رؤى قيمة وإرشادات عملية للباحثين والمهندسين والممارسين الساعين للاستفادة الكاملة من إمكانات اتصالات الجيل الخامس في عصر الموجات المليمترية

الكلمات المفتاحية: الجيل الخامس، هوائي الرقعة، هوائي المصفوفة، HFSS، الموجات المليمترية.

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List of Abbreviations

1G	First Generation Wireless Systems.
2G	Second Generation Wireless Systems.
3G	Third Generation Wireless Systems.
3GPP	Third Generation Partnership Project.
4G	Forth Generation Wireless Systems.
5G	Fifth Generation Wireless Systems.
AMTS	Automated Mass Transit System.
AMPS	Advanced Mobile Phone System.
BER	Bit-Error Rate.
BW	BandWidth.
CDMA	Code Division Multiple Access.
CDMA2000	Code Division Multiple Access 2000.
cMTC	Critical Machine Type Communications.
ETSI	European Telecommunications Standards Institute.
EDGE	Enhanced Data rates for GSM Evolution.
EM	Electromagnetic.
eMBB	Enhanced Mobile Broadband.
FNBW	First Null Beam-width.
GSM	Global System Mobile.
GPRS	General Packet Radio Service.
HSDPA	High-Speed Downlink Packet Access.
HSUBA	High-Speed Uplink Packet Access.
HPBW	Half-Power Beam-width.
iDEN	Integrated Digital Enhanced Network.
IP	Internet Protocol.
IoT	Internet of Things.

IMPS	Immediate Payment Service.
IMT	Institute of Management Technology.
ITU	International Telecommunication Union.
LTE	Long Term Evolution.
LOS	Line-of-Sight.
MTS	Mountain Time Standard.
MMS	Multimedia Messaging Services.
MIMO	Multiple Input Multiple Output.
mMTC	Massive Machine Type Communications.
MMIC	Monolithic Microwave Integrated Circuit.
MICs	Microwave Integrated Circuits.
NTT	Nippon Telephone &Telegraph.
N.M.T	Nordic Mobile Telephone.
OLT	Optical Line Terminal.
OFDM	Orthogonal Frequency Division Multiplexing.
PSTN	Public Switched Telephone Network.
PTT	Push-to-Talk.
PDC	Personal Digital Cellular.
SBSs	Small Base Stations.
TACS	Total Access Communication System.
TDMA	Time Division Multiple Access.
UMTS	Universal Mobile Telecommunication Service.
uRLLC	Ultra Reliable Low Latency Communications.
WAP	Wireless Application Protocol.
WCDMA	Wideband Code Division Multiple Access.
WiMAX	Worldwide Interoperability for Microwave Access.

General Introduction

In the ever-evolving landscape of wireless communication, the advent of 5G technology promises unprecedented advancements in speed, capacity, and connectivity. At the forefront of this technological revolution lies the design and optimization of patch antenna arrays, particularly in the millimeter-wave (mmWave) frequency range. This thesis embarks on a comprehensive exploration of patch antenna array design using High-Frequency Structure Simulator (HFSS), with a specific focus on their application in 5G networks.

Chapter 1 provides an introductory overview of mobile communication, tracing its evolution from its humble beginnings to the cutting-edge innovations of 5G technology. By understanding the historical context and underlying principles of mobile communication, we lay the foundation for exploring the challenges and opportunities presented by the 5G era.

In chapter 2, we delve into antenna theory, exploring the fundamental principles and concepts that underpin the design and operation of patch antennas. Topics covered include antenna types, radiation patterns, gain, polarization, and impedance matching. This theoretical groundwork equips us with the necessary knowledge to delve deeper into the design and optimization of patch antenna arrays in chapter 3.

Chapter 3 serves as the focal point of this thesis, where we dive into the intricacies of designing patch antenna arrays based on mmWaves for 5G applications. Leveraging the capabilities of HFSS, we explore various design methodologies, optimization techniques, and simulation tools to develop efficient and high-performing antenna arrays operating in the mmWave frequency range. Through detailed analysis and simulation results, we aim to unravel the complexities of array design and provide insights into the key factors influencing performance and reliability in 5G communication systems.

By synthesizing the insights gained from chapters 1 and 2 with the practical knowledge derived from chapter 3, this thesis aims to contribute to the advancement of patch antenna array design for 5G networks. Through rigorous analysis, simulation, and optimization, we strive to push the boundaries of antenna technology, enabling the realization of the full potential of 5G communication in the mmWave era.

Chapter 1

Evolution of mobile communications and 5G.

1.1 Introduction

The evolution of mobile communication has been a transformative journey from the rudimentary systems of the past to the advanced 5G networks of today. This chapter explores the historical progression of mobile technologies, highlighting key milestones that have shaped the industry. We will delve into the various use cases for 5G, demonstrating how it significantly enhances infrastructure and services. Additionally, a detailed performance comparison between 4G and 5G will be presented, emphasizing the superior capabilities of 5G in terms of speed, latency, and connectivity. The chapter will also examine the diverse applications of 5G, from smart cities to autonomous vehicles, and the critical technologies that underpin 5G, such as millimeter waves, massive MIMO, small cells, and beamforming. Through this comprehensive overview, we aim to provide a clear understanding of how 5G is set to revolutionize mobile communication and its broader impact on various sectors.

1.2 Evolution of mobile communications

Mobile communication technologies have gone through several stages or generations of evolution and improvement in their performance which are divided as follows [1]:

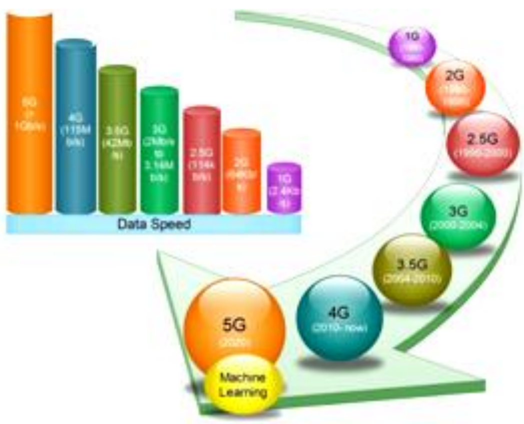

Figure 1. 1 Development of wireless network from 1G to 5G with years and data speed [2].

1.2.1 Zero generation wireless communication (0G)

The pre-cellular or "0G" system, developed after World War II, was an early form of mobile communication. It relied on manual connections and limited frequencies, enabling only a few simultaneous calls. The bulky "car phones" used were integrated with the public switched telephone network (PSTN), allowing calls to any connected phone. Despite lacking modern features like data capabilities and frequency switching, 0G technologies such as MTS, IMPS, and PTT laid the groundwork for future mobile communication. Early adopters included professionals who needed mobile communication, and sales channels included specialized radio carriers and telephone companies. Though limited, 0G established the principle of wireless communication, paving the way for the cellular networks that followed [2].

1.2.2 First generation wireless communication (1G)

The first generation of cellular technology, known as 1G, ushered in the era of mobile communication in the 1980s, quickly becoming the dominant force throughout the 1990s. Japan was at the forefront of this revolution, with NTT launching the world's first commercial mobile system in Tokyo in 1979. Europe followed suit with the development of various analog systems, including N.M.T. (Nordic Mobile Telephone) in Scandinavia, TACS (Total Access Communication System) in the UK, and systems like C450 in countries like Portugal, South Africa, and West Germany. These 1G networks used analog radio signals to transmit voice calls, offering a limited range of functionalities and struggling with issues like low bandwidth, unstable handoff, weak voice connections, and a lack of encryption, making them vulnerable to interference and security breaches. In the United States, AMPS (Advanced Mobile Phone Service) was introduced in 1982, establishing a standard for 1G networks that utilized a 40 MHz bandwidth within the 800/900 MHz frequency spectrum. Despite its limitations, 1G paved the way for the advancements of subsequent generations, laying the foundation for the modern mobile communication landscape we know today [2].

1.2.3 Second generation wireless communication (2G)

The second generation of cellular technology, 2G, emerged in the early 1990s, marking a significant shift from analog to digital communication. This advancement brought about a new era of mobile communication, characterized by increased network efficiency, data services, and widespread adoption. Finland's Radiolinja, later known as Elisa Oyj, became a pioneer in commercializing 2G networks based on the GSM standard in 1991. This period saw the rise of various 2G technologies, including GSM, PDC, iDEN, and iS-136, all utilizing TDMA (Time Division Multiple Access). GSM, the most widely adopted 2G standard, allowed for universal roaming, enabling users to use their phones across a vast network of countries. In North America, the Digital AMPS

(IS-54 and IS-136) standards were also widely used, employing TDMA to multiplex calls on a single frequency. The introduction of CDMA (Code Division Multiple Access) technology with the IS-95 standard marked a departure from TDMA, providing greater capacity and improved security. 2G ushered in a new era of mobile communication, making mobile phone ownership more accessible and offering functionalities beyond simple voice calls, including text messaging and basic data services. This era laid the foundation for the future advancements of 3G, 4G, and 5G networks.

2.5G, primarily defined by the General Packet Radio Service (GPRS), served as a crucial transitional phase between the voice-focused 2G and the data-centric 3G networks. Built upon the existing GSM infrastructure, GPRS introduced packet-switched data communication, allowing for more efficient use of bandwidth and enabling faster data transfer speeds, ranging from 56 kbps to 384 kbps. This technology paved the way for a new generation of data-driven applications, including the Wireless Application Protocol (WAP) for mobile internet access, Multimedia Messaging Service (MMS) for sharing multimedia content, and basic email and web browsing capabilities. Developed by the European Telecommunications Standards Institute (ETSI) and now managed by the Third Generation Partnership Project (3GPP), GPRS played a significant role in the evolution of mobile communication, bridging the gap between the voice-centric era and the data-driven future.

2.75G, also known as EDGE (Enhanced Data rates for GSM Evolution), represented a significant advancement over traditional 2G networks, particularly GPRS. Introduced in 2000, EDGE built upon the existing GSM infrastructure, offering significantly faster data speeds and enhanced communication capabilities. This technology achieved these improvements through the implementation of 8-phase shift keying encoding, allowing for three bits of data to be transmitted per symbol while maintaining the same symbol rate. This enhancement allowed for higher data transfer speeds, making EDGE a valuable technology for transmitting information and data more effectively. Also known as Enhanced GPRS or IMT Single Carrier, EDGE became a popular choice for mobile phone networks, enabling more robust data communication capabilities and paving the way for the further development of 3G networks [2].

1.2.4 Third generation wireless communication (3G)

The third generation of cellular technology, 3G, emerged in the early 2000s, ushering in a new era of mobile communication characterized by significantly enhanced data capabilities and a wider range of services. The International Telecommunication Union (ITU) played a crucial role in establishing a global standard for 3G networks, proposing a frequency band in the 2000 MHz range and promoting a single, standardized wireless communication protocol across the globe. This led to the development of various 3G technologies, including

CDMA2000, an evolution of Code Division Multiple Access, which utilized IS-95 and IS-95B technologies. GSM's 3G evolution, known as IS136, and the PDC System contributed to the development of Wideband Code Division Multiple Access (WCDMA), also referred to as Universal Mobile Telecommunication Service (UMTS). Both CDMA2000 and WCDMA emerged as dominant 3G technologies, further solidifying the 3GPP's (Third Generation Partnership Project) efforts to standardize mobile communication. 3G systems significantly expanded the capabilities available to users, offering high-speed data connections, enabling mobile voice calls, video calls, internet access, and even mobile television services. The introduction of 3.5G, often called High-Speed Downlink Packet Access (HSDPA), and 3.75G, also known as High-Speed Uplink Packet Access (HSUPA), marked further advancements, increasing data speeds and improving overall network performance. These enhancements ultimately paved the way for the development of 4G (LTE) technology, which eventually superseded 3.75G [2].

1.2.5 Fourth generation wireless communication (4G)

4G technology builds upon 3G wireless networks by offering significantly increased bandwidth and a broader range of services. While initially marketed as 4G, LTE did not fully meet the technological specifications at its inception. However, through its evolution to LTE Advanced, it has become a dominant 4G standard. WiMax, another 4G contender, gained initial traction but has not achieved widespread adoption. The key technologies enabling 4G's high speeds and performance are MIMO (multiple inputs, multiple outputs) and OFDM (orthogonal frequency division multiplexing). 4G aims to deliver high-quality, high-speed internet data services, improving network security and enabling seamless internet access over IP. Compared to 3G's peak speed of 2 Mbps, 4G boasts significantly higher data rates, reaching up to 100 Mbits/sec for fast-moving users and 1Gbits/sec for stationary or low-mobility users. However, real-world speeds can vary considerably due to network congestion, signal strength, and device capabilities [2].

1.2.6 Fifth generation wireless communication (5G)

Fifth-generation (5G) wireless communications are the future of reliable wireless communications, with a high data rate of >10 GB/s (compared to 1 GB/s for 4G) and low latency < 1ms (compared to 70 ms of 4G) to accommodate the ever-increasing telecommunication traffic. Key technologies that will play an important role in 5G communications are millimetre waves, massive MIMO, small base stations (SBSs), and beamforming. Small Cell Base Stations (SBSs) with multiple and distributed antennas having high gain and directional radiation patterns, together with efficient beamforming techniques will play a fundamental role in high data rate transmission. Currently allocated frequency spectrum is reaching its capacity limit, so cellular systems will have to move to higher frequency bands beyond 3 GHz and up to 300 GHz to access wider continuous channel bandwidth, increased network capacity, and to meet expected growth. Therefore, the bands at millimetre-wave frequencies have been proposed for next-generation wireless communications such as 24.25-29.5 GHz, and 37-40 GHz. Implementation of mm-Wave 5G communication systems will be made possible with the development of new design and modelling techniques as well as fabrication methods. Table 1.1 provides comparisons between mobile generations [3].

Technology	1G	2G	3G	4G	5G
Start year	1970-1990	1990-2004	2004-2010	2010-2020	2020
Frequency band	150 MHz-9000 MHz	(800-900) MHz (1800-1900) MHz	(800-900) MHz (1600-2000) MHz	2 GHz-8 GHz	3 GHz-300 GHz
Data rate	2 Kbps	64 Kbps-144 Kbps	2 Mbps	100 Mbps-1Gbps	Higher than 10 Gbps
Technology	Analog	Digital	UMTS, CDMA2000	LTE,WiFi, WiMax	WWWW
Switching	Circuit	Circuit Packet	Packet	Packet	Packet
Multiplexing	FDMA	TDMA, FDMA	CDMA	OFDM	OFDM
Primary services	Analog Phone Calls	Digital Phone Call, Messages	Data, MMS, Phone Calls,SMS	IP Services	Large Broadcasting

Table 1.1 Comparison between mobile generations [1].

1.3 Use case for 5G

5G offer significant advancements for smart grid infrastructure compared to wired systems, improving speed, and efficiency, reducing delays, and lowering implementation costs. 5G technologies can be categorized into four types [4]:

- **mMTC (massive Machine Type Communications)** : Supports a large number of Internet of Things (IoT) devices, crucial for managing smart grid infrastructure's basic level, such as smart sensors and meters .

- **uRLLC (Ultra Reliable Low Latency Communications):** Minimizes operational delays, essential for high-speed processing in modern smart grid systems .

- **eMBB (enhanced Mobile Broadband):** Provides high bandwidth necessary for increased processing power, movie playback, and online display-based applications, potentially enabling fiber optic-like speeds for mobile devices.

These 5G technologies, with their specific strengths, offer a powerful and flexible framework for improving smart grid infrastructure and enabling a more efficient and responsive power grid .

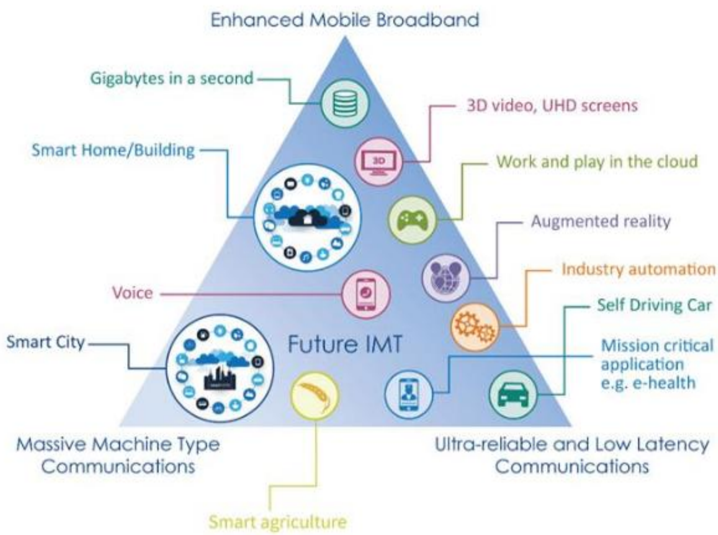

Figure 1.2 The 5G use case.

1.4 Performance comparison of 5G Vs 4G

Features	4G	5G
Maximum Data Rate	1 Gbps	10 Gbps
Latency	10 ms	<1 ms
Frequency band	Sub-3 GHz	Sub-6 GHz, mmWave (24-100 GHz)
Bandwidth	Up to 20 MHz	Up to 400 MHz
Connection Density	100,000 devices per km²	1,000,000 devices per km²
Energy Efficiency	Moderate	High

Table 1.2 Comparison between 4G and 5G technologies.

1.5 Applications of 5G

Many applications can be supported by 5G networks as represented in the following sections:

1.5.1 Smart cities

5G enables the development of smart cities through enhanced connectivity for smart infrastructure, traffic management, and public safety.

1.5.2 Autonomous vehicles

With its low latency and high reliability, 5G is crucial for the operation of autonomous vehicles, allowing real-time communication between vehicles and infrastructure.

1.5.3 Healthcare

5G supports telemedicine, remote surgeries, and real-time patient monitoring, transforming the healthcare industry.

1.6 Technical component of 5G

In this section, we present some important technical components of 5G network:

1.6.1 Millimetre-wave (mm-Wave)

Electromagnetic (EM) waves with frequencies between 30 GHz and 300 GHz have free space wavelengths between 1 and 10 millimeters, giving them the name millimeter waves. This part of the EM spectrum is underused and can be utilized for 5G applications. Due to the rapid increase in wireless data traffic, mm-Wave technology is used for 5G mobile communication to provide high data rate communication services. Figure 1.3 shows the mmWaves band between THz band and microwave band [5].

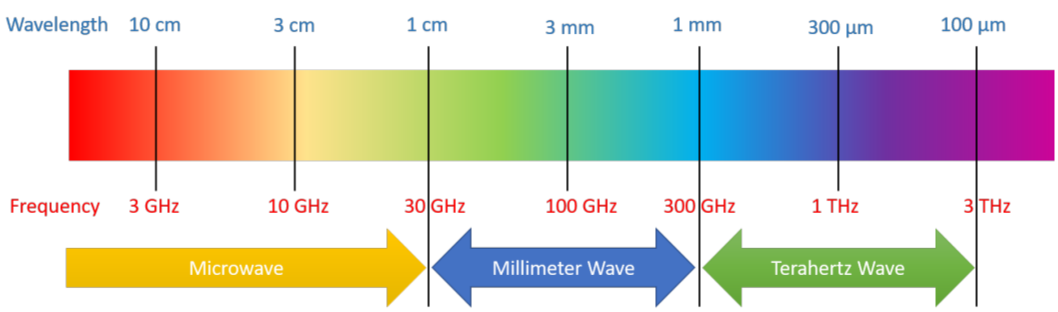

Figure 1.3 Millimetre wave band [6].

Advantages and disadvantages of millimeter-wave communications can be summarized as following [5]:

- One of the major benefits of mm-wave communication is the availability of large bandwidth to support extremely high data rate transmission, which is a key requirement in future 5G communications. Figure 1.4 presents the 5G network coverage range.

Figure 1.4 5G Network coverage ranges.

- At mm-wave frequencies the size of a single antenna element will be very small, hence the small size of individual antennas will lead to less space occupied by the arrays in comparison to a lower frequency.

- Co-channel interference to and from other systems would be mitigated due to Line-of-Sight (LOS) propagation by using highly directional and steerable antenna arrays.

- Large capacity of users would be possible in a 5G network due to the large frequency reuse factor. Figure 1.5 shows how mmWaves increase the system capacity.

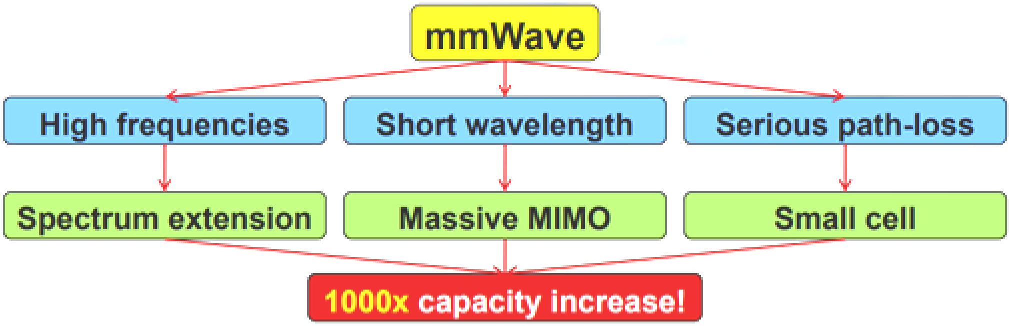

Figure 1.5 Capacity increasing using mmWaves [7].

- According to the Friis equation, signals in the mm-wave band experience higher free space path loss, as well as large attenuation due to atmospheric absorption when compared to lower frequencies. Therefore, reliable communication with low Bit-Error Rate (BER) mm-wave communication can only be possible at short distances < 100 meters.

- Transmission quality of mm-wave communication can be negatively affected by ground obstacles, buildings, and trees. In addition, heavy rainfall and fog conditions can also degrade the performance of millimetre wave communication

1.6.2 Massive MIMO

Both MIMO and Massive MIMO are integral to the development of 5G networks. While MIMO provides significant improvements in capacity, efficiency, and performance over traditional single-antenna systems, Massive MIMO offers exponential gains by leveraging a large number of antennas to achieve unprecedented levels of capacity, spectral efficiency, and energy efficiency. The choice between MIMO and Massive MIMO depends on specific deployment requirements, cost considerations, and performance goals. As 5G technology continues to evolve, Massive MIMO is expected to play a crucial role in meeting the increasing demands for higher data rates and more reliable wireless communication. Table 1.3 shows a comparison between MIMO and Massive MIMO.

Feature	MIMO	Massive MIMO
Basic Concept	Utilizes multiple antennas at both transmitter and receiver (e.g., 2x2, 4x4 configurations).	Extends MIMO with a much larger number of antennas (tens or hundreds) at the base station.
System Capacity	Enhances system capacity by exploiting spatial diversity.	Significantly increases capacity and efficiency through precise beamforming and spatial multiplexing.
Spectral Efficiency	Provides moderate improvements in spectral efficiency.	Achieves much higher spectral efficiency by serving multiple users simultaneously.
Energy	Improves energy efficiency to some	Offers substantial improvements in energy

Efficiency	extent.	efficiency through precise beamforming.
Interference Management	Manages interference with spatial filtering techniques.	Manages interference more effectively due to a large number of antennas enabling advanced suppression techniques.
Beamforming	Directs signals towards specific users to improve signal quality.	Uses highly directional and adaptive beams for enhanced coverage and reliability.
Complexity and Cost	Moderate increase in hardware complexity and cost.	Significantly increases hardware complexity and cost due to numerous antennas and advanced signal processing.
Deployment Scenarios	Suitable for a wide range of scenarios, including urban and rural environments.	Ideal for dense urban environments and high user density areas requiring substantial capacity improvements.

Table 1.3 Comparison between MIMO and Massive MIMO.

1.6.3 Small cells

Small cells are low-powered cellular radio access nodes that help improve coverage and capacity in densely populated urban areas.

1.6.4. Beamforming

Beamforming is a technique that directs signals to specific users rather than broadcasting in all directions, enhancing signal strength and reducing interference.

1.7 Conclusion

This chapter has traced the remarkable evolution of mobile communication, from its early stages to the cutting-edge 5G technology. We have seen how each generation has built upon the previous one, bringing significant advancements in speed, connectivity, and capabilities. The performance improvements of 5G over 4G, coupled with its diverse applications and enabling technologies, underscore its potential to revolutionize numerous industries. As we transition into the next chapter on antenna fundamentals, it becomes evident that understanding the underlying principles of antenna design is crucial. Antennas play a pivotal role in realizing the full potential of 5G, particularly in leveraging technologies like millimeter waves and massive MIMO. By exploring antenna fundamentals, we will gain deeper insights into how these components enhance the performance and efficiency of 5G networks.

Chapter 2

Antenna fundamentals

2.1 Introduction

This chapter provides an in-depth exploration of various types of antennas, which are fundamental components in wireless communication systems. We begin with a detailed look at different antenna types, including wire antennas, aperture antennas, reflector antennas, lens antennas, microstrip antennas, and array antennas. Each of these antenna types serves distinct purposes and applications, contributing uniquely to the performance and efficiency of communication systems. Following this, we delve into the specifics of microstrip patch antennas, examining their advantages and disadvantages, and discussing the concept of multi-band microstrip patch antennas, which enhance versatility and functionality. The chapter further covers crucial antenna parameters such as radiation pattern, beamwidth, directivity, antenna efficiency, gain, polarization, bandwidth, and input impedance, all of which are essential for understanding and optimizing antenna performance. Additionally, various feeding methods, including microstrip line feed, coaxial feed, proximity coupling, and aperture coupling, are explained to provide insights into how antennas are energized. Finally, the chapter discusses methods of analysis, focusing on fringing effects, effective length and resonant frequency, and effective width, offering a comprehensive framework for analyzing and designing efficient antenna systems. This foundational knowledge will pave the way for deeper insights into advanced antenna technologies and their applications in modern communication networks.

2.2 Principe and definition

Antennas function as reciprocal devices, capable of both transmitting and receiving electromagnetic waves. They act as transitional structures, converting guided waves from transmission lines (such as coaxial cables or waveguides) into free-space waves, and vice versa as in Figure 2.1. This conversion occurs in a specific region, enabling the transfer of energy between the guiding structure and open space. To analyze antenna behavior, we can model the system as an electrical circuit. In transmission mode, a Thevenin equivalent representation consists of a source (ideal generator), a transmission line with its characteristic impedance, and the antenna, represented as a load with complex impedance as in Figure 2.2. This impedance includes radiation resistance (representing radiated energy), loss resistance (accounting for energy loss within the antenna structure), and reactance (associated with energy storage). Ideally, all energy from the source would be directed into the radiation resistance, maximizing the antenna's radiating efficiency. However, in practical systems, losses occur due to conduction and dielectric materials, along with impedance mismatches between the transmission line and antenna.

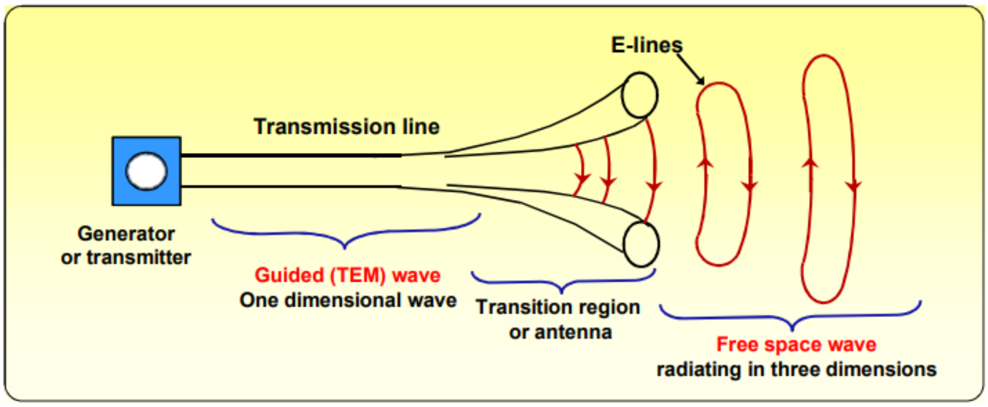

Figure 2.1 Antenna as a transition device [8].

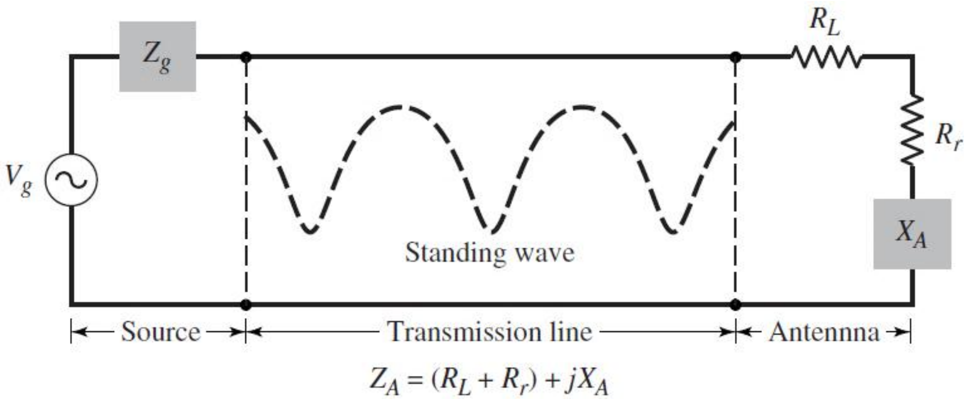

Figure 2.2 Transmission-line Thevenin equivalent of the antenna in transmitting mode [9].

2.3 Types of antennas

In the following sections, we delve into the different types of antenna:

2.3.1 Wire antenna

Wire antennas are ubiquitous and recognizable to most people, as they can be found on automobiles, buildings, ships, aircraft, and even spacecraft. These antennas come in various shapes, including straight wires (dipoles), loops, and helices, as illustrated in Figure 2.3. Loop antennas, for example, are not limited to circular shapes; they can also be rectangular, square, elliptical, or any other configuration. Circular loops are particularly common due to their straightforward construction [9].

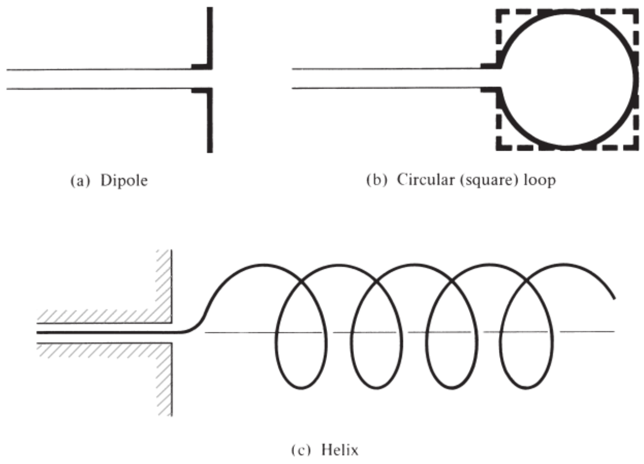

Figure 2.3 Wire antenna configurations [9].

2.3.2 Aperture antennas

Aperture antennas are gaining recognition among the general public, particularly as there is a growing need for advanced antenna designs and higher frequency applications. Figure 2.4 illustrates some examples of aperture antennas. These antennas are particularly advantageous for aircraft and spacecraft applications as they can be seamlessly integrated into the vehicle's skin. Moreover, they can be coated with a dielectric material to shield them from environmental hazards[9].

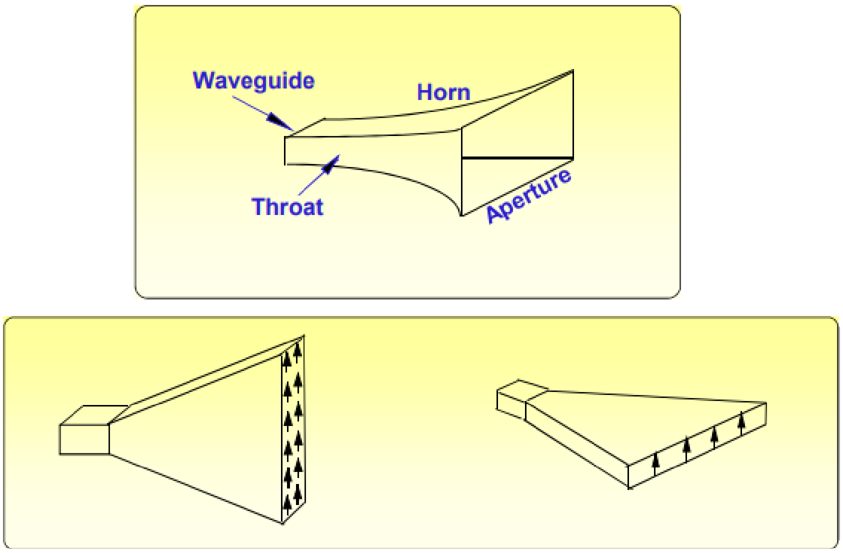

Figure 2.4 Aperture antennas [8].

2.3.3 Reflector antennas

The success in the exploration of outer space has resulted in the advancement of antenna theory. Because of the need to communicate over great distances, sophisticated forms of antennas had to be used in order to transmit and receive signals that had to travel millions of miles. A very common antenna form for such an application is a parabolic reflector shown in Figures 2.5. Antennas of this type have been built with diameters of 305 m or even larger. Such large dimensions are needed to achieve the high gain required to transmit or receive signals after millions of miles of travel. Another form of a reflector, although not as common as the parabolic, is the corner reflector [9].

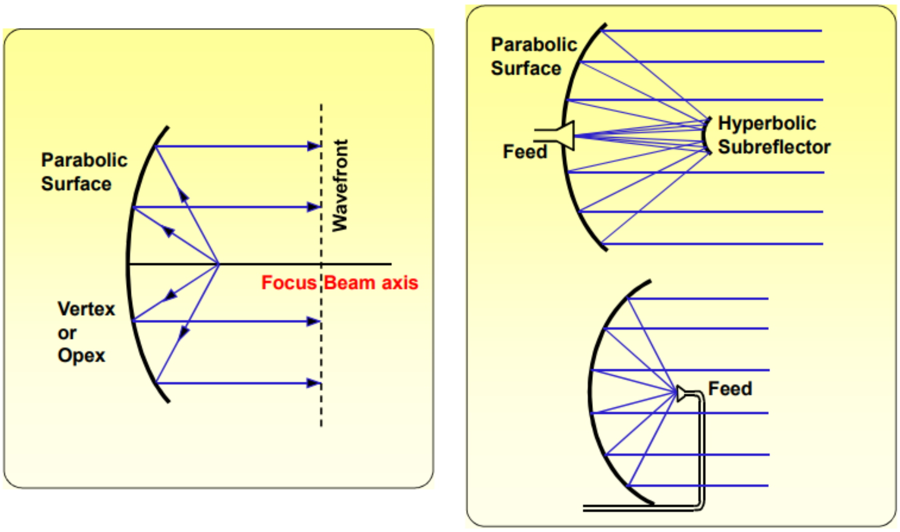

Figure 2.5 Typical reflector configurations [8].

2.3.4 Lens antennas

Lenses are primarily used to collimate incident divergent energy to prevent it from spreading in undesired directions. By properly shaping the geometrical configuration and choosing the appropriate material of the lenses, they can transform various forms of divergent energy into plane waves. They can be used in most of the same applications as are the parabolic reflectors, especially at higher frequencies. Their dimensions and weight become exceedingly large at lower frequencies. Lens antennas are classified according to the material from which they are constructed, or according to their geometrical shape. Some forms are shown in Figure 2.6.

In summary, an ideal antenna is one that will radiate all the power delivered to it from the transmitter in a desired direction or directions. In practice, however, such ideal performances cannot be achieved but may be closely approached. Various types of antennas are available and each type can take different forms in order to achieve the desired radiation characteristics for the particular application [9].

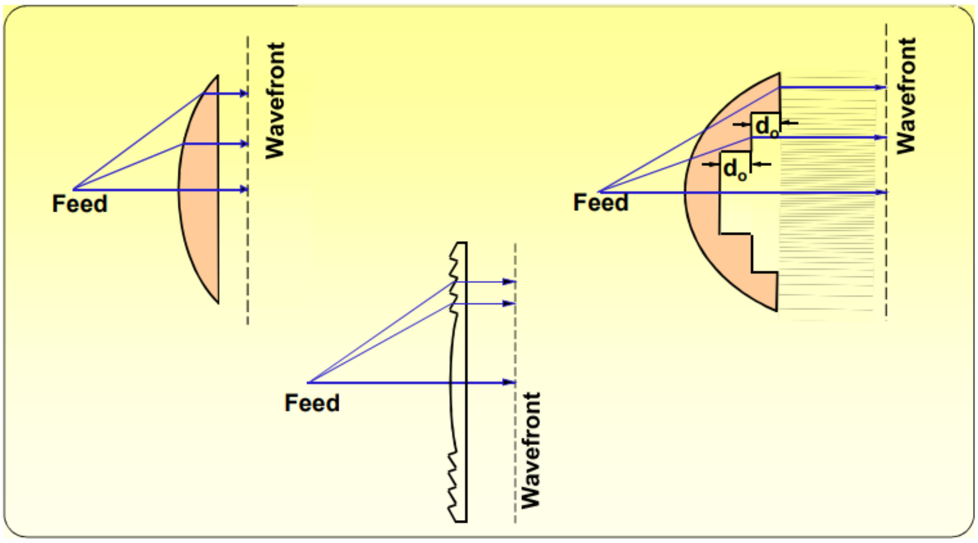

Figure 2.6 Typical lens antenna configurations [8].

2.3.5 Microstrip antennas

Microstrip antennas became very popular in the 1970s primarily for spaceborne applications.

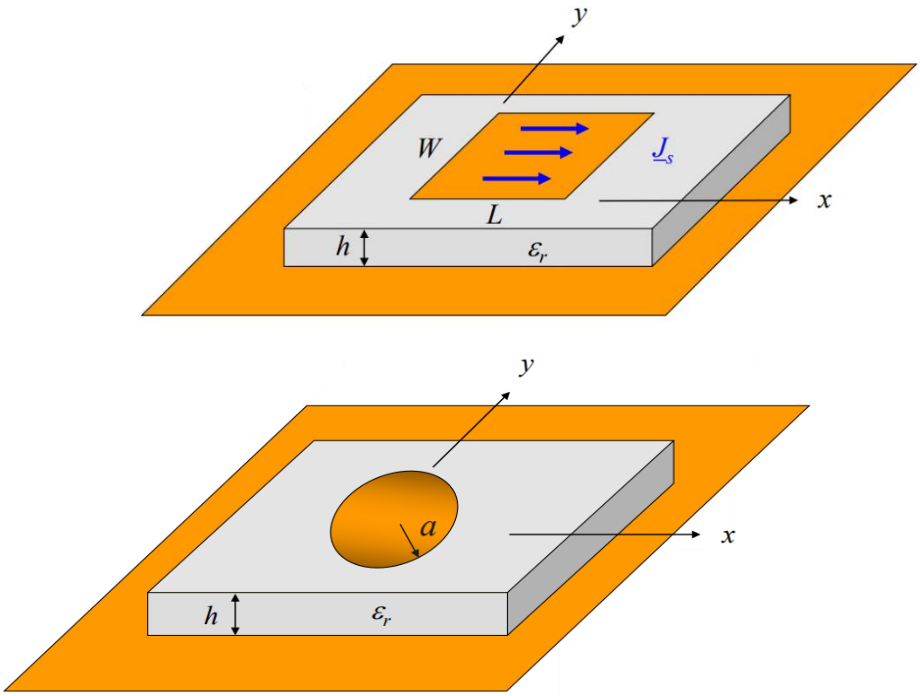

Figure 2.7 Rectangular and circular microstrip (patch) antennas [10].

Today they are used for government and commercial applications. These antennas consist of a metallic patch on a grounded substrate. The metallic patch can take many different configurations. However, the rectangular and circular patches, shown in Figure 2.7, are the most popular because of ease of analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. The microstrip antennas are low profile, conformable to planar and nonplanar surfaces, simple and inexpensive to fabricate using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, compatible with MMIC designs, and very versatile in terms of resonant frequency, polarization, pattern, and impedance. These antennas can be mounted on the surface of high-performance aircraft, spacecraft, satellites, missiles, cars, and even mobile devices [9].

2.3.6 Array antennas

Many applications require radiation characteristics that may not be achievable by a single element. It may, however, be possible that an aggregate of radiating elements in an electrical and geometrical arrangement (an array) will result in the desired radiation characteristics.

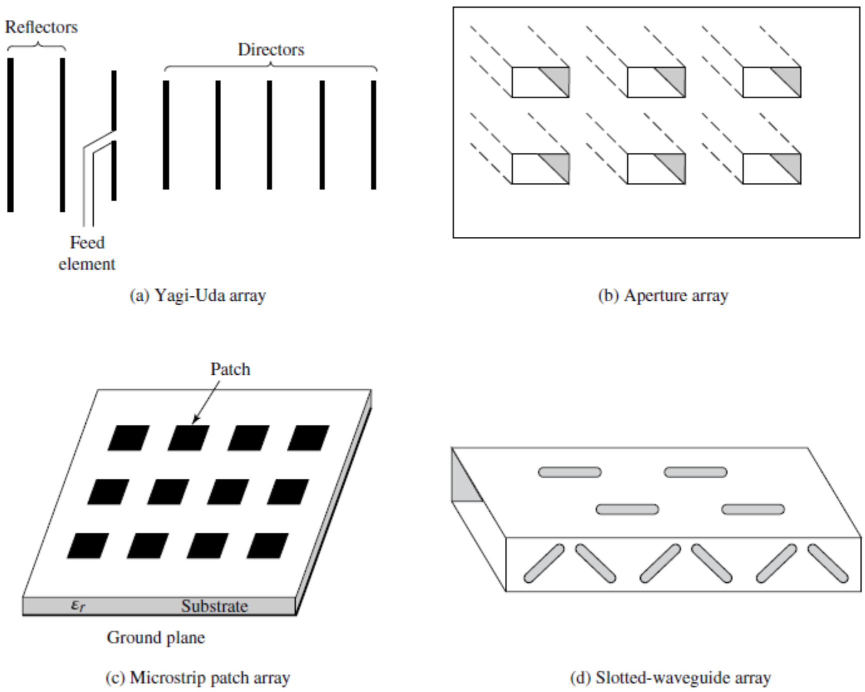

Figure 2.8 Typical wire, aperture, and microstrip array configurations [9].

The arrangement of the array may be such that the radiation from the elements adds up to give a radiation maximum in a particular direction or directions, minimum in others, or otherwise as desired. Typical examples of arrays are shown in Figure 2.8 Usually, the term array is reserved for an arrangement in which the individual radiators are separate as shown in Figures 2.8(a–c). However the same term is also used to describe an assembly of radiators mounted on a continuous structure, shown in Figure 2.8(d) [9].

2.4 Microstrip patch antenna

In its most fundamental form, a Microstrip Patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Figure 2.9. The patch is generally made of conducting material such as copper or gold and can take any possible shape. The radiating patch and the feed lines are usually photo-etched on the dielectric substrate.

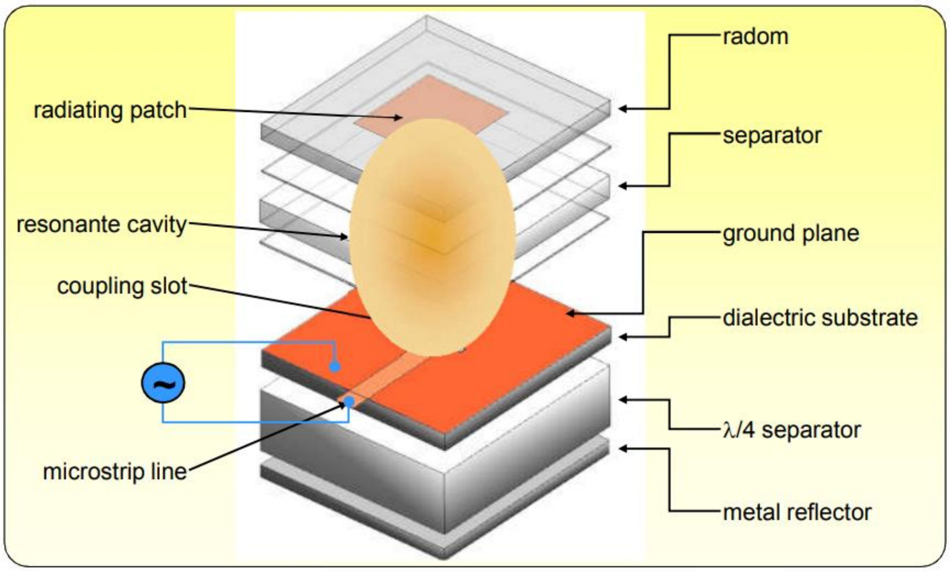

Figure 2.9 Structure of a microstrip patch antenna.[8].

In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular, and elliptical or some other common shape as shown in Figure 2.9. For a rectangular patch, the length L of the patch is usually$0.3333\lambda_o \leq L \geq 0.5\lambda_o$, where $\lambda_o$is the free-space wavelength. The patch is selected to be very thin such that $t \ll \lambda_o$(where t is the patch thickness). The height h of the dielectric substrate is usually$0.003\lambda_o \leq h \geq 0.05\lambda_o$. The dielectric constant of the substrate (ε_r) is typically in the range$2.2 \leq \varepsilon_r \geq 12$.

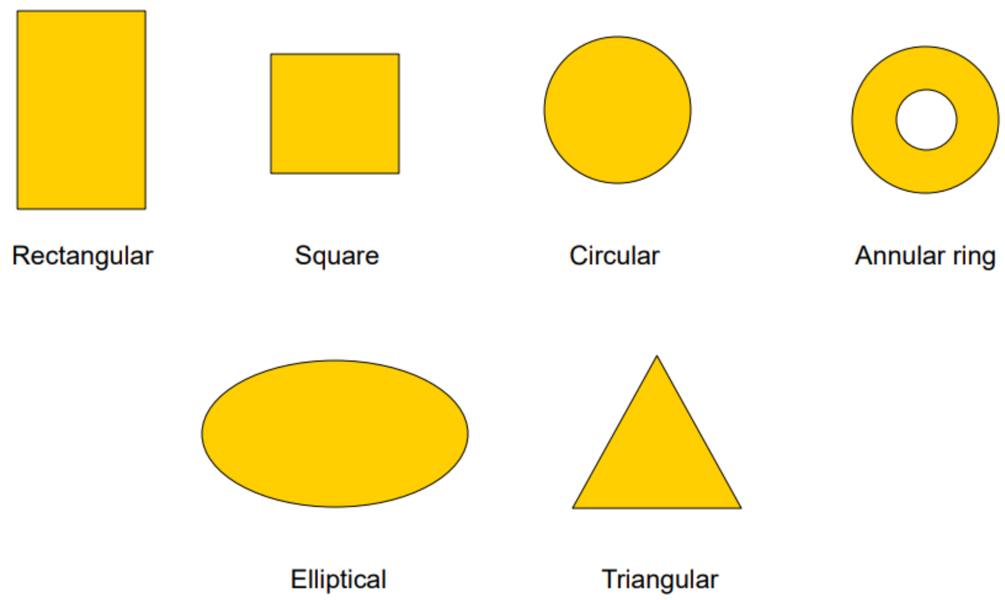

Figure 2.10 Common shapes of microstrip patch element [10].

Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation. However, such a configuration leads to a larger antenna size. In order to design a compact Microstrip patch antenna, substrates with higher dielectric constants must be used which are less efficient and result in narrower bandwidth. Hence a trade-off must be realized between the antenna dimensions and antenna performance [11].

2.4.1 Advantages and disadvantages

Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc. The telemetry and communication antennas on missiles need to be thin and conformal and are often in the form of Microstrip patch antennas. Another area where they have been used successfully is in Satellite communication. Some of their principal advantages discussed by Kumar and Ray are given below:

- Light weight and less volume.
- Low fabrication cost, therefore can be manufactured in large quantities.
- Supports both, linear as well as circular polarization.
- Low profile planar configuration which can be easily made conformal to host surface.
- Can be easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.

- Mechanically robust when mounted on rough surfaces.

Microstrip patch antennas suffer from more drawbacks as compared to conventional antennas. Some of their major disadvantages are given below:

- Narrow bandwidth
- Low efficiency
- Low Gain
- Low power handling capacity.
- Surface wave excitation
- Extraneous radiation from feeds and junctions
- Poor end fire radiator except tapered slot antennas

Microstrip patch antennas have a very high antenna quality factor (Q). It represents the losses associated with the antenna where a large Q leads to narrow bandwidth and low efficiency. Q can be decreased by increasing the thickness of the dielectric substrate. But as the thickness increases, an increasing fraction of the total power delivered by the source goes into a surface wave [11].

2.5 Multi-band microstrip patch antenna

A multi-band microstrip patch antenna is a compact and versatile antenna that efficiently operates at multiple frequencies. This design, a variation of the standard microstrip patch antenna, utilizes clever modifications to achieve its multi-band functionality. Its small size, lightweight construction, and low-cost fabrication process using printed circuit boards make it suitable for various applications with space constraints, including mobile devices, satellite communication, and wearable technology. The multi-band capability allows for the transmission and reception of different signals using a single antenna, streamlining system design and reducing overall costs. These advantages make the multi-band microstrip patch antenna a valuable solution for applications requiring compact, cost-effective, and versatile antennas.

2.6 Antenna parameters

This section presents antenna parameters to understand and characterize the antenna performance when designing and measuring antennas [1].

2.6.1 Radiation pattern

The antenna radiation pattern can be defined as a graphical representation of radiated properties (power/field) as a function of the angular space. The mean of the radiated properties is the magnitude of electric or the magnetic field. When we plot the magnitude of the electric or the magnetic field we have the field pattern and when we plot the square of electric or the magnetic field we have the power pattern coordination.

The radiation pattern can be separated to various radiation lobes, where the lobe containing the direction of the maximum radiation is called the main lobe or the major lobe and the other lobes are called minor lobes (back or side lobe) as shown in Figure 2.11. Moreover, we find nulls between the lobes, where the field goes to zero[1].

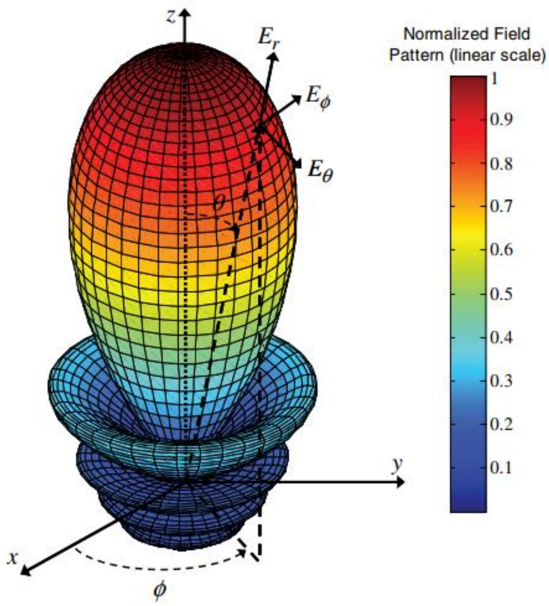

Figure 2.11 Radiation pattern.

There are three major shapes of radiation patterns depending on the direction of the radiation [1]:

- **Isotropic:** It is the radiation pattern of an ideal antenna which has equal radiation in all directions. Its shape looks like a ball .
- **Omin-directional:** It is the radiation pattern of an antenna which has equal radiations in a given plane and directional radiations in any orthogonal plane. Its shape looks like a donut.
- **Directional:** It is the radiation pattern of an antenna which has effectively radiation in some directions than other directions.

2.6.2 Beamwidth

The beam-width of an antenna is the angular separation between two identical points on opposite side of the pattern maximum. Many beam-widths are found in the antenna pattern but the most important one is the Half-Power Beamwidth (HPBW).

HPBW contains the direction of the maximum of the antenna beam, and it is defined as the angle between the two identical points in which the radiation intensity in one-half value of the beam. There is another important beam-width which is the First Null Beamwidth (FNBW) that is defined as the angular separation between the first nulls of the patterns. See Figure 2.12 and 2.13.

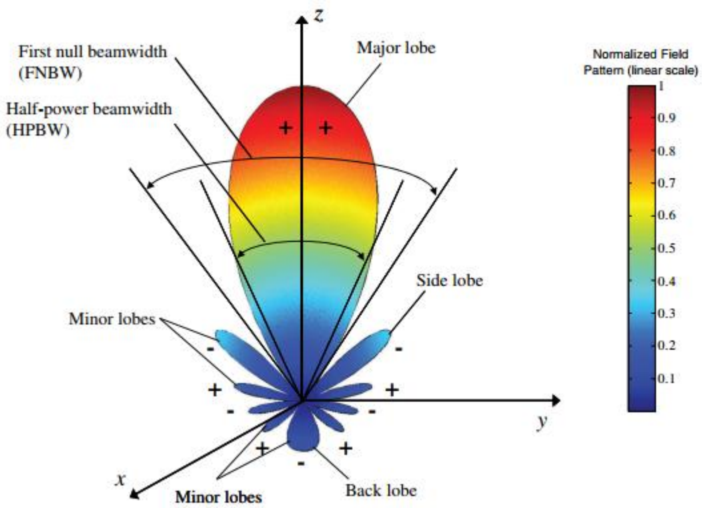

Figure 2.12 HPBW & FNBW [1].

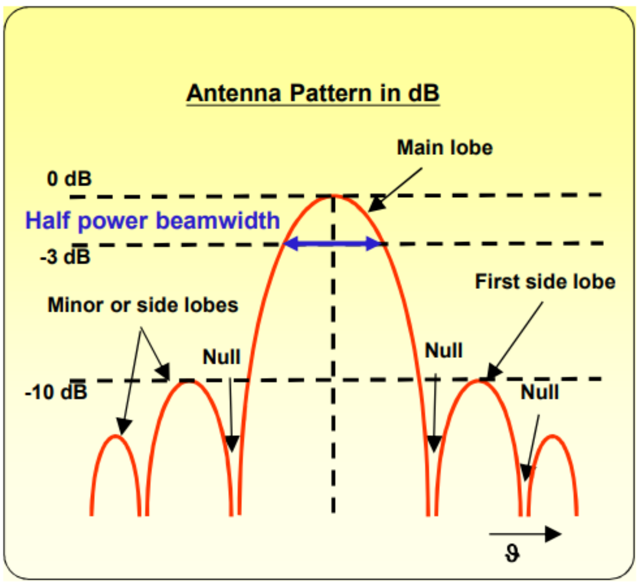

Figure 2.13 Antenna radiation pattern with lobes and beamwidths [8].

2.6.3 Directivity

The directivity is an important parameter and it is defined as the ratio of the maximum radiation intensity of designed antenna to the isotropic radiation intensity. The radiation intensity (U) is the total power radiated by the designed antenna per unit solid angel. In mathematical form [1]:

$$Directivity = \frac{Max\, radiation\, intensity\, of\, designed\, antenna}{Radiation\, intensity\, of\, isotropic\, antenna} \qquad (2.1)$$

$$D = \frac{U}{U_o} = \frac{4 \times \pi \times U}{P_{rad}} \qquad (2.2)$$

- D: Directivity.
- U: Radiation intensity of the designed antenna.
- U_o: Radiation intensity of the isotropic antenna.
- P_{rad}: Total radiation power.

2.6.4 Antenna efficiency

The antenna efficiency can be defined as the ratio of the output power (radiated power) of the antenna to the input power to the antenna. In mathematical form:

$$Efficiency\ (\eta) = \frac{Radiated\ Power\ (P_{rad})}{Input\ power\ (P_{input})} \qquad (2.3)$$

Referring to the losses in the power are caused by the mismatching between the antenna and the transmission line, also losses occur in conduction and dielectric materials [1].

2.6.5 Gain

The antenna gain can be defined as the ratio of the radiation intensity of designed antenna to the desired direction to the isotropic radiation intensity. So it is too close to the directivity in definition but the simple difference between them is that the directivity considers the input power equals to the radiated power but the gain takes the efficiency of antenna in the calculation as shown in its mathematical expression [1].

$$Gain\ (G) = \ (Efficiency\ (\eta))\ \times (Directivity\ (D)). \qquad (2.4)$$

The units for antenna gain listed are in dB, dBi , or dBd. The definitions of terms are [1]:

- $\boldsymbol{dB}-$ **decibels**. (i.e. 10 dB means 10 times the energy relative to an isotropic antenna in the peak direction of radiation) .
- $\boldsymbol{dBi}$- **"decibels relative to an isotropic antenna"**. 3 dBi means twice (2x) the power relative to an isotropic antenna in the peak direction .
- $\boldsymbol{dBd}$- **"decibels relative to a dipole antenna".** Note that a half-wavelength dipole antenna has a gain of 2.15 dBd Hence, 7.85 dBd means the peak gain is 7.85 dB higher than a dipole antenna; this is 10 dB higher than an isotropic antenna .

2.6.6 Polarization

The polarization of an electromagnetic wave follows the direction of the electric field. So, we can define antenna polarization as the polarization of the transmitted waves from the antenna in the designed direction. The polarization of a plane wave in Figure 2.14 shows that the instantaneous electric field traces out with time at a fixed observation point.
The spatial behavior of the electric and magnetic fields of a linearly(vertical) polarized wave for a fixed instant of time .

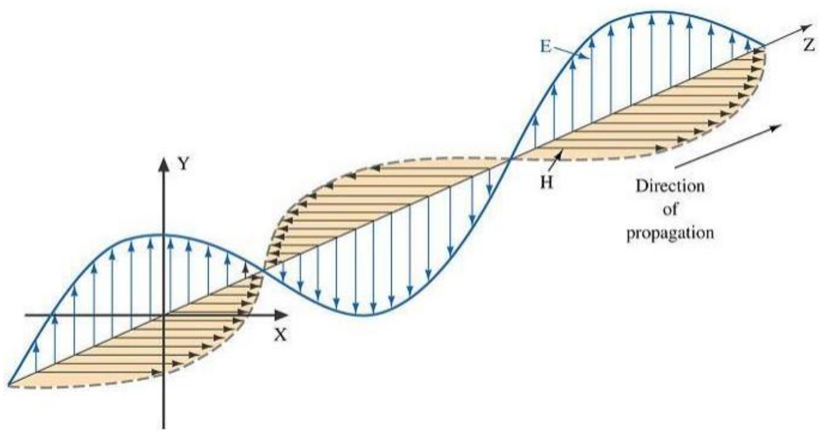

Figure 2.14 The polarization of a wave plan [12].

- **Linear polarization:** the electric field's vector stays in the same plane and move in straight line at every instant time. It has two type of polarization (vertical and horizontal) as shown in Figure 2.15.

- **Circular polarization:** the electric field's vector moves in as a function of time. The field has two orthogonal components which much have the same magnitude. The effect of multi-path is reduced so it is used in the satellite communication. It has two type of polarization (left-hand circular polarizations and right-hand circular polarization) as shown in Figure 2.15 .

- **Elliptical polarization:** It is the same as the circular polarization but the magnitudes of the two orthogonal components of the field are not the same. So, we can see that the linear and the circular polarization can be considered as a special case of the Elliptical polarization. It has two type of polarization (left-hand elliptical polarizations and right-hand elliptical polarization) as shown in Figure 2.15.

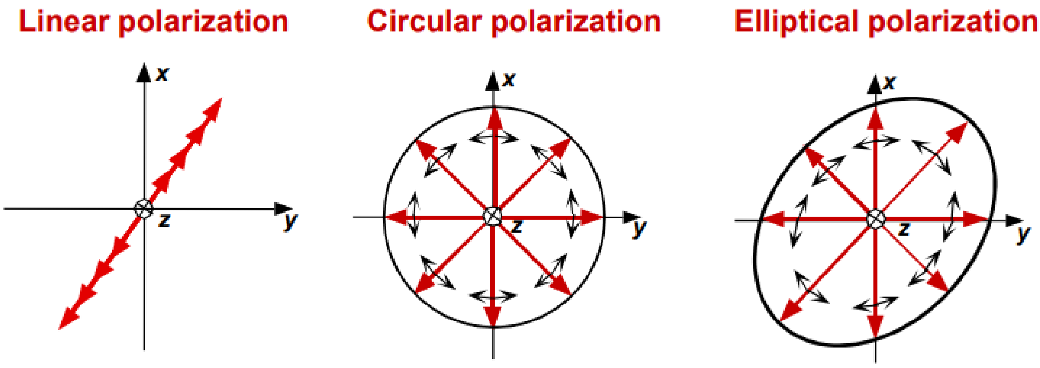

Figure 2.15 Type of polarization [8].

2.6.7 Bandwidth

The antenna bandwidth (BW) can be defined as the range of frequencies on the two sides of the resonant frequency of the antenna where the values of all the antenna parameter are acceptable like (Gain, Input impedance, Polarization, ...etc.) and its usually taken under $-10\ dB$ value of the scattering parameter (S11) as shown in Figure 2.16 .

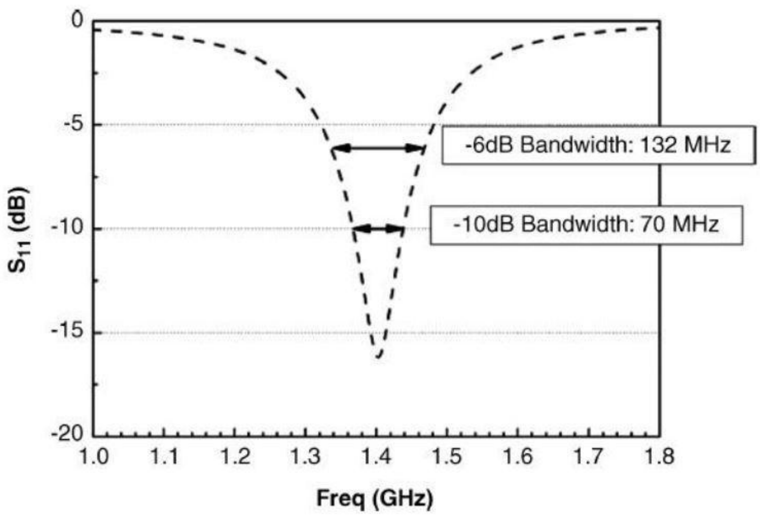

Figure 2.16 Antenna bandwidth [1].

2.6.8 Input Impedance

The input impedance of an antenna can be defined as the ratio of the voltage to the current between two terminals or it is the impedance between the antenna terminals, where the antenna can be modeled as an equivalent electrical circuit as shown in Figure 2.17 .

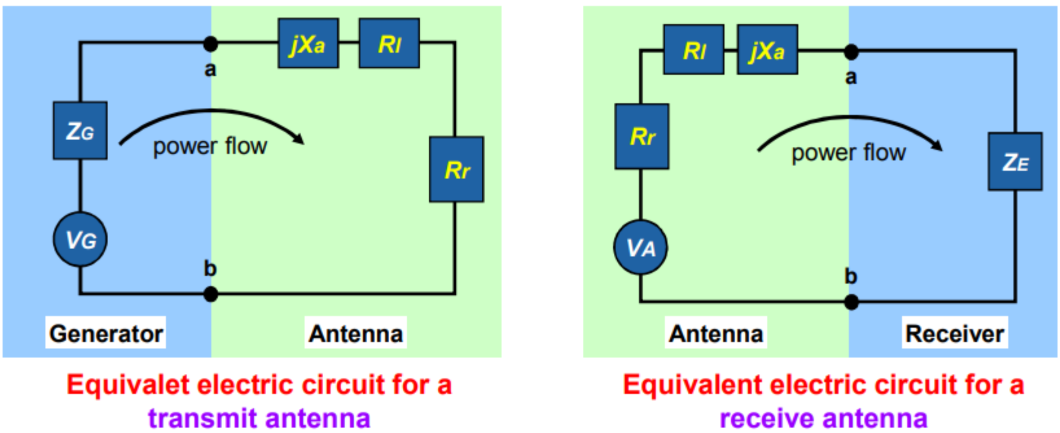

Figure 2.17 Equivalent electric circuits for transmit and receive antennas [8].

$$Z_A = R_A + jX_a \tag{2.5}$$

$$R_A = R_L + R_r \tag{2.6}$$

Where:

Z_A: Antenna input impedance.

R_r: Radiation resistance.

R_L: Series resistance (losses).

X_a: Reactance due to stored energy.

2.7 Feeding methods

There are many methods of feeding a microstrip antenna. The most popular methods are:

1. Microstrip Line.
2. Coaxial Probe (coplanar feed).
3. Proximity Coupling.
4. Aperture Coupling.

Because of the antenna is radiating from one side of the substrate, so it is easy to feed it from the other side (the ground plane), or from the side of the element .

2.7.1 Microstrip line feed

This method of feeding is very widely used because it is very simple to design and analyze and very easy to manufacture. Figure 2.18 shows a patch with microstrip line feed from the side of the patch .

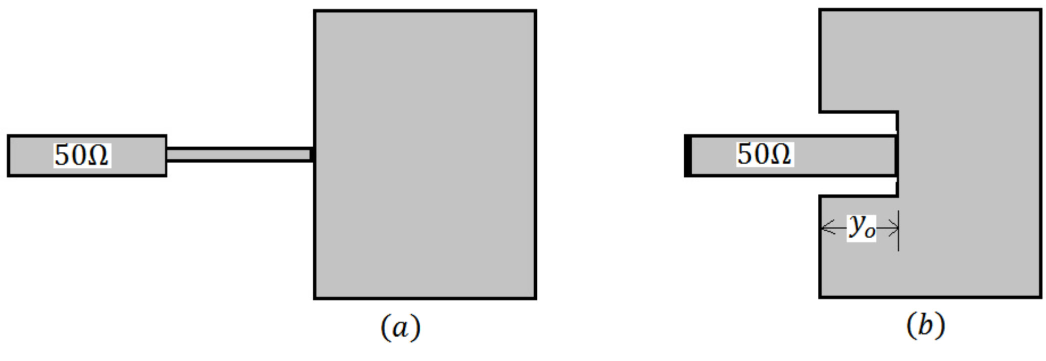

Figure 2.18 Microstrip patch antenna with feed from the side [13].

The feeding technique of the patch in Figure 2.18a and Figure 2.19 is widely used in both one patch antenna and multi-patches (array) antennas .

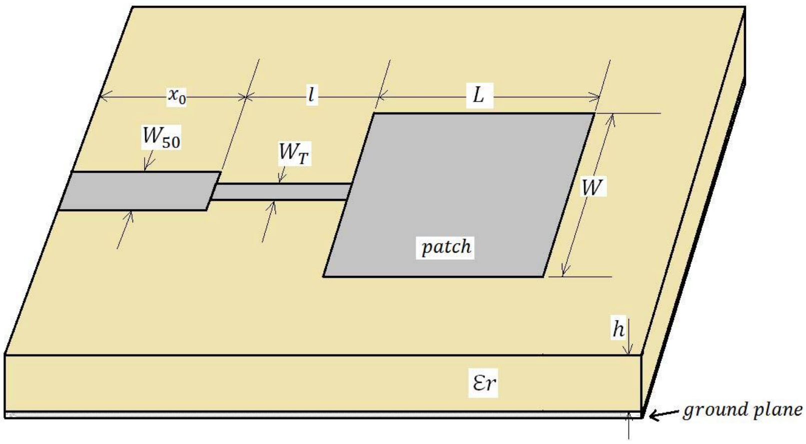

Figure 2.19 Rectangular microstrip patch antenna[13].

The impedance of the patch is given by [13]:

$$Z_a = 90\frac{{\varepsilon_r}^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2 \tag{2.7}$$

The characteristic impedance of the transition section should be[13]:

$$Z_a = \sqrt{50 + Z_T} \tag{2.8}$$

The width of the transition line is calculated from [13]:

$$Z_T = \frac{60}{\sqrt{\varepsilon_r}}\ln\left(\frac{8d}{w_T} + \frac{w_T}{4d}\right) \tag{2.9}$$

The width of the 50 Ω microstrip feed can be found using the equation (2.10)[13]:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{reff}}\left(1.393 + \frac{w}{h} + \frac{2}{3}\ln\left(\frac{w}{h} + 1.444\right)\right)} \tag{2.10}$$

Where $Z_0 = 50\,\Omega$.

The length of the strip can be found from (2.11)[13].

$$R_{in(x=0)} = \cos^2\left(\frac{\pi}{L}x_0\right) \tag{2.11}$$

The length of the transition line is quarter the wavelength [13]:

$$l = \frac{\lambda}{4} = \frac{\lambda_o}{4\sqrt{\varepsilon_{reff}}} \tag{2.12}$$

2.7.2 Coaxial feed (Coplanar feed)

Coupling of power to the patch antenna through a probe is very simple, cheap, and effective way. If the designer adjusts the feed point to 50 Ω, so he just needs to use a 50 Ω coaxial cable with an N-type coaxial connector.

The N-coaxial connector is coupled to the back side of the microstrip antenna (the ground plane) and the centre connector of the coaxial will be passed through the substrate and soldered to the patch, as shown in the Figure 2.20.

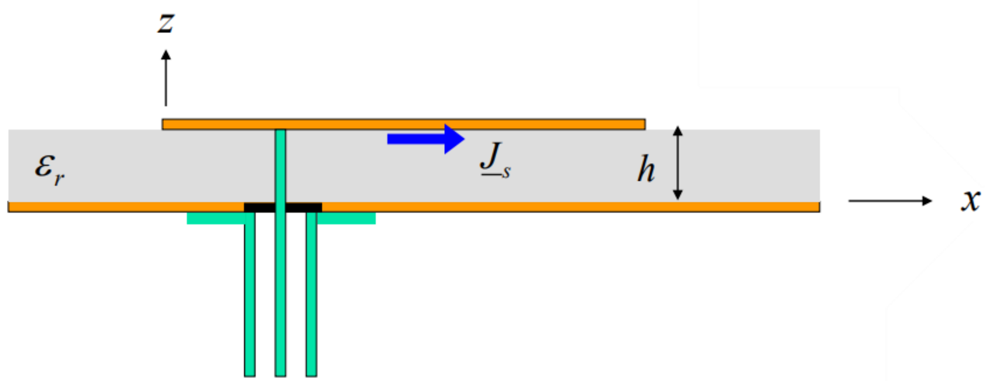

Figure 2.20 Coaxial line feed [10].

2.7.3 Proximity coupling

Proximity coupling is used two substrates ε_{r1} and ε_{r2}. The patch will be on the top, the ground plane at the bottom, and a microstrip line is connected to the power source and lying between the two substrates as shown in the Figure 2.21 This type is known also as electromagnetically coupled microstrip feed.

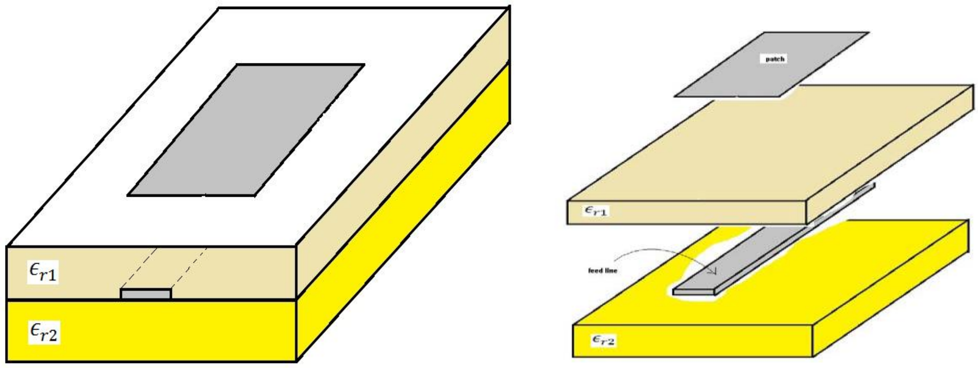

Figure 2.21 Proximity coupling feed method[13].

The principle of this mechanism is that the behavior between the patch and the feed strip line is capacitive. Analysis and design of such an antenna is a little more complicated than the others discussed in the previous sections because the designer has to take into account the effect of the coupling capacitor between the strip feed line and the patch as well as the equivalent $R_L - C$ resonant circuit representing the patch and the calculating of two substrates ($\varepsilon_{r1} and\ \varepsilon_{r2}$)The coupling capacitor of this antenna can be designed for impedance matching of the antenna [13].

2.7.4 Aperture coupling

Figure 2.22 shows the layers of the microstrip patch antenna using the aperture mechanism.

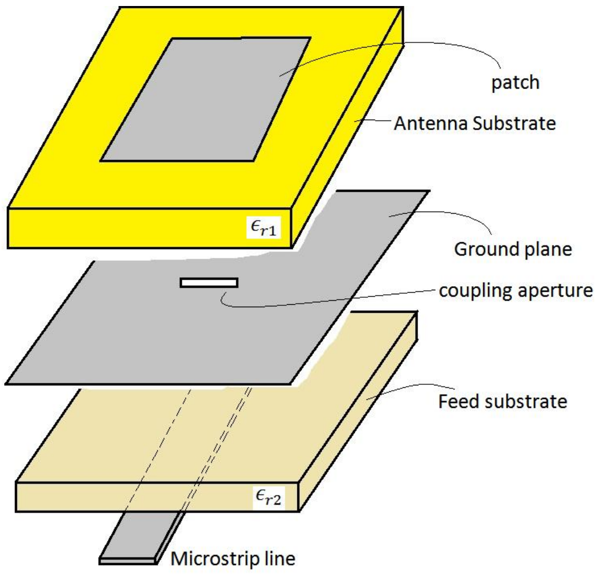

Figure 2.22 Aperture coupling feed method[13].

The ground plane has an aperture in a shape of a circle or rectangular, and separates two substrates: the upper substrate $\varepsilon_{r1}$with the patch on it, and the lower substrat ε_{r2} with the microstrip feed line under it. This type of coupling gives wider bandwidth. Another property of this type is the radiating of the feeding strip line is reduced by the shielding effect of the ground plane. This feature improves the polarization purity [13].

2.8 Method of analysis

There are many methods of analysis for microstrip antenna. Comparing to other methods, the transmission line method is the easiest method. It gives good physical insight, representing the rectangular patch as a pair of two radiating slots, separated by a low-impedance (Zc) transmission line of certain length L. However, this method is less accurate and it is more difficult to model coupling [14].

2.8.1 Fringing effects

Because the dimensions of the patch are finite along the length and width, the fields at the edges of the patch undergo fringing. It is the fringing fields that are responsible for the radiation. This is illustrated along the length in Figure 2.23 for the two radiating slots of the microstrip antenna. The amount of fringing is a function of the dimensions of the patch and the height of the substrate. For the principal E-plane, fringing is a function of the ratio of the length of the patch L to the height h of the substrate (L/h) and the dielectric constant ε_r of the substrate. Since for microstrip antennas $L/h \gg 1$, fringing is reduced. However, it must be taken into account because it influences the resonant frequency of the antenna. Because of the fringing effect, in which some of the waves travel in the substrate and some in air, an effective dielectric constant ε_{reff} is introduced to account for this effect [14].

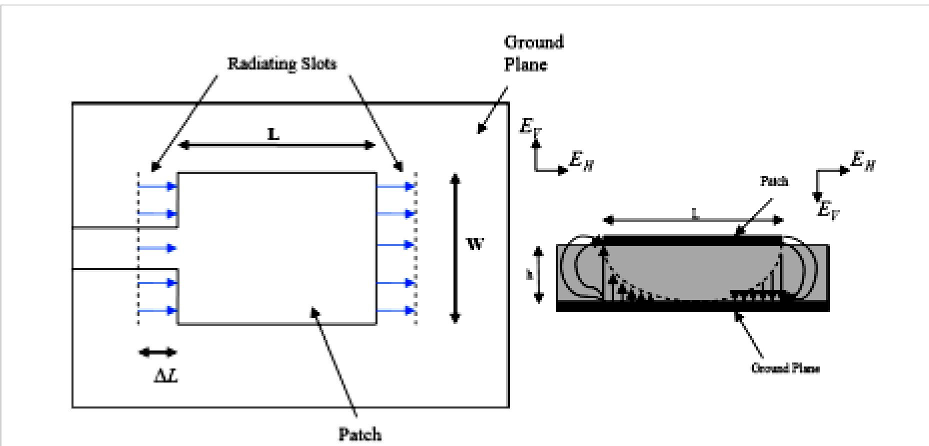

Figure 2.23 Microstrip antenna and its electric field lines [14].

The effective dielectric constant is defined as the dielectric constant of the uniform dielectric material so that the electric field lines have identical electrical characteristics, particularly the propagation constant, as the actual field line.
The value of the effective dielectric constant is essentially constant at low frequencies, then increasing monotonically as the frequency increases, and ends up approaching the value of the dielectric constant of the substrate at higher frequencies. The initial values (at low frequencies) of the effective dielectric constant are referred to as the static values, and they are given by [14]:

$$\varepsilon_{reff} = \frac{\varepsilon_r - 1}{2} + \frac{\varepsilon_r + 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{2.13}$$

Where

ε_{reff}: Effective dielectric constant.
ε_r: Dielectric constant of substrate.
h : Height of dielectric substrate.
w: Width of the patch.

With $w/h > 1$

2.8.2 Effective length and resonant frequency.

In the transmission line model (Figure 2.25), the antenna is represented by two radiating slots ($W \times h$) separated by a low impedance transmission line (Zc) of length L. The slots represent very high-impedance terminations from both sides of the transmission line (almost an open circuit). Thus, we expect this structure to have highly resonant characteristics depending mainly on its length L. Due to the fringing effect, the resonant length of the patch is not exactly equal to the physical length. The fringing effect makes the physical length of antenna shorter than the effective electrical length of the patch. The dimensions of the patch along its length have been elongated on each end by a length of ΔL, which is a function of the effective dielectric constant $\varepsilon reff$ and the width-to-height ratio (W/h). A well-known and practical approximate relation for the normalized extension of the length show as follows [14]:

$$L_{eff} = (L + 2\Delta\mathrm{L}) \tag{2.14}$$

$$L_{eff} = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}\sqrt{\varepsilon_{reff}}} = \frac{v_o}{2f_r\sqrt{\varepsilon_{reff}}} \tag{2.15}$$

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{2.16}$$

Dominant TM_{010} mode f_r is

$$f_{r010} = \frac{1}{2\text{L}\sqrt{\mu_o \varepsilon_o \sqrt{\varepsilon_r}}} = \frac{v_o}{2\text{L}\sqrt{\varepsilon_r}} \qquad (2.17)$$

Where v_o is the speed of light in free space. The resonant frequency of a patch depends highly on L. Because (2-5) does not account for fringing, it must be modified to include edge effects and when the fringing effect is taken into account, (2-5) becomes [14].

$$f_{r010} = \frac{1}{2L_{eff}\sqrt{\mu_o \varepsilon_o}\sqrt{\varepsilon_{reff}}} = \frac{1}{2(L+2\Delta L)\sqrt{\mu_o \varepsilon_o}\sqrt{\varepsilon_{reff}}} \qquad (2.18)$$

$$= q\frac{1}{2L\sqrt{\mu_o \varepsilon_o}\sqrt{\varepsilon_r}} = q\frac{v_o}{2L\sqrt{\varepsilon_r}}$$

Where

$$q = \frac{f_{rc010}}{f_{r010}} \qquad (2.19)$$

The q factor is referred to as the fringe factor (length reduction factor). As the substrate height increases, fringing also increases and results in larger separations between the radiating edges and lower resonant frequencies [14].

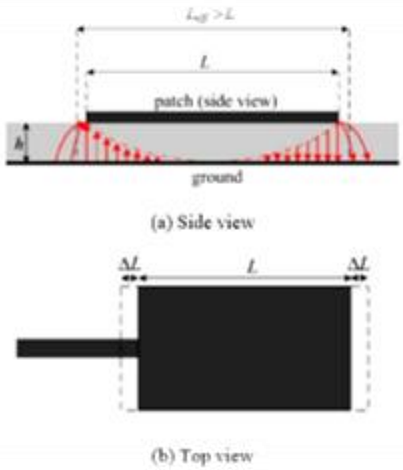

Figure 2.24 Physical and effective lengths of rectangular microstrip patch antenna [14].

2.8.3 Effective width

For an effective radiator, a practical width that leads to good radiation efficiencies is [14]:

$$W = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2.20}$$

Calculate the actual (physical) length of the patch using (2-14), (2-15) and (2-16)

$$L = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{2.21}$$

$$= \frac{v_o}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L$$

2.9 Conclusion

In conclusion, this chapter has thoroughly examined the various types of antennas and their fundamental characteristics, highlighting the crucial role they play in wireless communication systems. We explored a wide range of antennas, from traditional wire and aperture antennas to modern microstrip and array antennas, each with its unique applications and benefits. The discussion on microstrip patch antennas, including their advantages, disadvantages, and multi-band capabilities, provided a detailed understanding of this versatile antenna type. Furthermore, we delved into essential antenna parameters and various feeding methods, offering insights into the critical factors that influence antenna performance and efficiency. The methods of analysis discussed in this chapter equip us with the necessary tools to evaluate and optimize antenna designs.

Chapter 3

Patch antenna arrays based mmWaves for 5G.

3.1 Introduction

With this comprehensive foundation, we are now well-prepared to explore more advanced topics. The next chapter will focus on the design of 5G patch antenna arrays, an area of significant importance for the development of next-generation wireless networks. We will delve into the specific design considerations, techniques, and innovations required creating efficient and high-performing 5G antenna arrays, ensuring robust and reliable communication in the evolving technological landscape.

This chapter focuses on the various design methods for creating effective patch antennas, crucial for the development of 5G communication systems. We begin by outlining general design methods, setting the stage for more specific discussions. The chapter then delves into the basic design of simple patch antennas, starting with the design and simulation of a simple patch antenna, followed by a detailed analysis of its simulation results. Building on this, we explore the E-shape slotted patch antenna, which is designed to improve performance characteristics, and we present its corresponding simulation results to highlight these enhancements. Moving forward, the chapter addresses the design of antenna arrays, starting with array antenna with two elements design and its simulation results, and then progressing to the more complex array antenna with four elements design, accompanied by its simulation outcomes. Through detailed examples and simulation data, this chapter provides a comprehensive guide to the design and optimization of single-element and array antennas, essential for achieving the high performance required in modern wireless communication networks.

3.2 Basics of simple antenna design

To create a rectangular patch antenna tailored for 5G communication systems, we begin by selecting the substrate and identifying the resonant frequency, which is 38 GHz. Following this, the dimensions of the antenna are calculated.

This design employs a low-loss Teflon-based RT/Duroid 5880 substrate, featuring a dielectric constant of 2.2 and a thickness of 0.254 mm.

From equation (2.20) we calculate W:

$$W = \frac{1}{2f_r\sqrt{\varepsilon_o\mu_o}}\sqrt{\frac{1}{\varepsilon_r+1}} = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{3.1}$$

$$= \frac{3\times10^8}{2\times38\times10^9}\sqrt{\frac{2}{1+2.2}}$$

$$= 3.12\ mm$$

To find the effective dielectric constant, ε_{reff}, and when $W/h > 1$, we can use (2-13):

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{3.2}$$

$$= \frac{2.2+1}{2} + \frac{2.2-1}{2}[1+12\frac{0.254}{3.12}]^{-\frac{1}{2}}$$

$$= 2.027$$

This value for ε_{reff} is reasonable, because $1 \leq \varepsilon_{reff} \leq \varepsilon_r$.

The effective length can be found using (2-14), (2-15) and (2-16):

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{reff}}} \tag{3.3}$$

$$= \frac{3\times10^8}{2\times38\times10^9\sqrt{2.027}}$$

$$= 2.772\ mm$$

$$\varDelta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{3.4}$$

$$= 0.412\times0.254\times10^{-3}\frac{(2.027+0.3)\left(\frac{3.12}{0.254}+0.264\right)}{(2.027-0.258)\left(\frac{3.12}{0.254}+0.8\right)}$$

$$= 0.132\ mm$$

The actual length of the patch can be found from (3.5):

$$L = L_{eff} - 2\Delta L = 2.772 - 0.132 = 2.64\ mm \quad (3.5)$$

3.3 Design of simple patch antenna

In this design, we concentrate on a single-band antenna operating at 37.8 GHz. Subsequently, a slot will be incorporated into the patch to enable the antenna to function on an additional frequency band. To enhance matching and increase antenna bandwidth, a gap-coupled feed line is utilized. Figure 3.1 illustrates the single-element patch antenna without slots, while Table 1 details the antenna's dimensions.

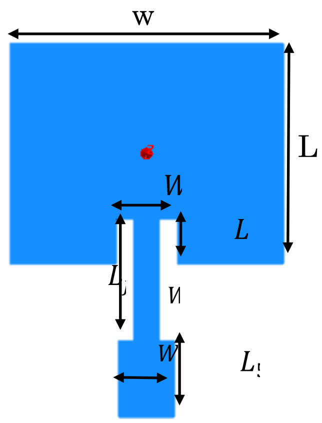

Figure 3. 1 Structure of simple patch antenna structure.

Parameters	**Values (mm)**
W	3.12
L	2.64
W_c	0.7
L_c	0.57
W_f	0.298
L_f	1.38
W_{50}	0.6372
L_{50}	0.87

Table 3.1 Dimensions of the simple patch antenna.

Using HFFS, this antenna has been designed. As shown in the simulated result for the single band single element the magnitude of the S_{11} parameter has good result which equals to -30 dB at 37.8 GHz (Figure 3.7) with large -10 dB bandwidth of 1.3 GHz. The three-dimensional radiation pattern for the single element single band (37.8 GHz) is shown in Figure 3.9. The maximum realized gain for the non-slotted patch is 9.44 dBi at 37.8 GHz.

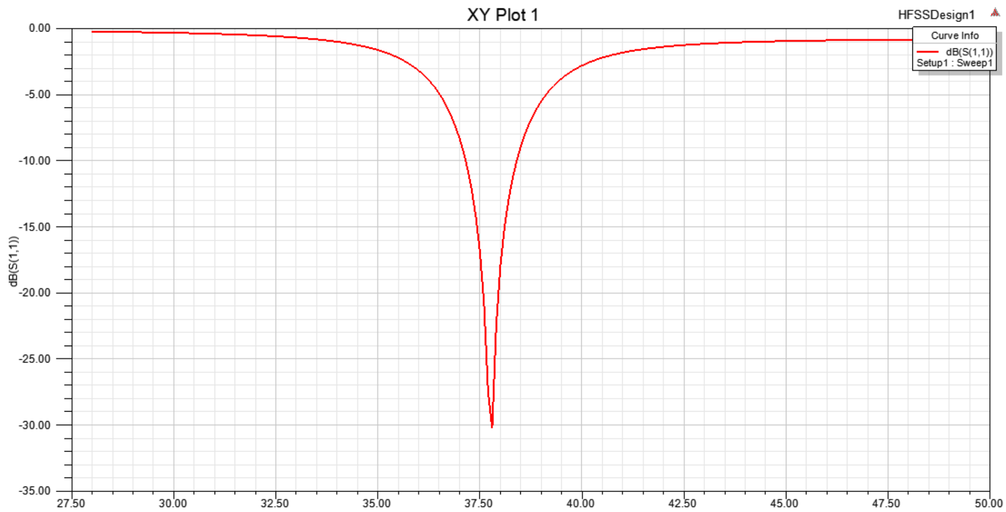

Figure 3. 2 S_{11} results for simple patch antenna.

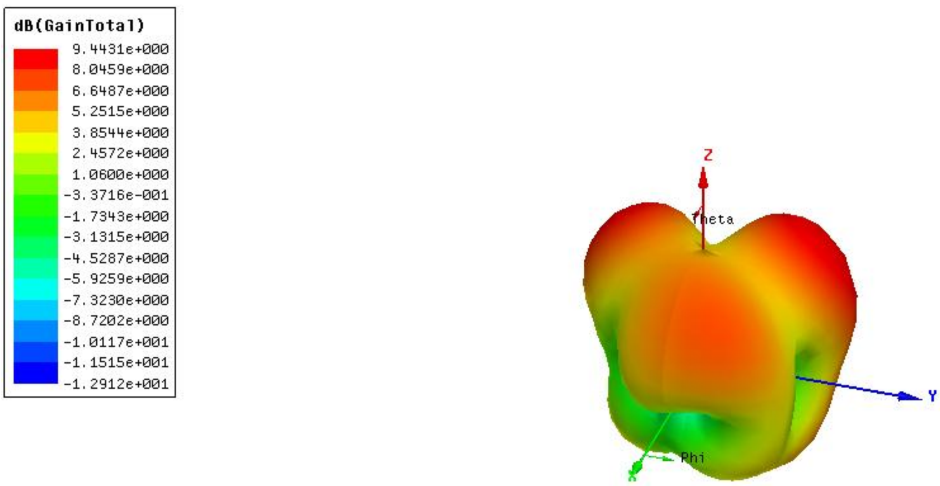

Figure 3.3 Total gain of simple patch antenna.

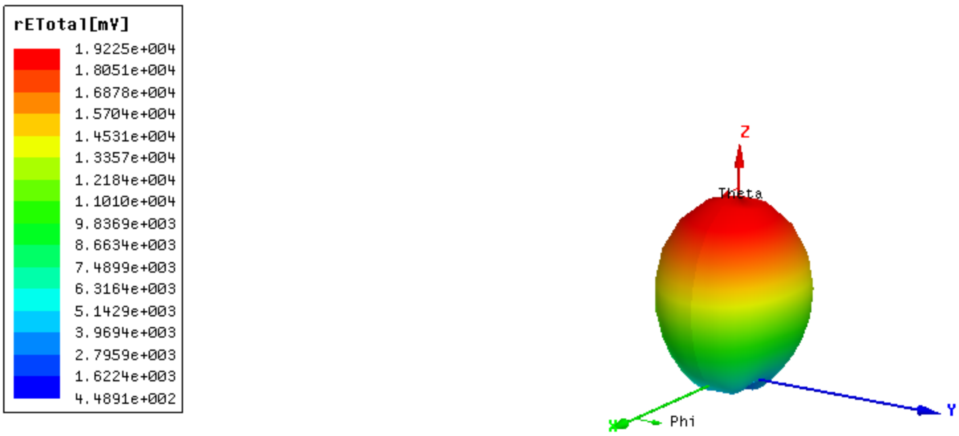

Figure 3.4 Radiation pattern of simple patch antenna.

3.4 Design of patch antenna with E-shape slot

To achieve dual-band capability in a microstrip patch antenna for 5G communication systems, an E-shaped slot has been introduced on the patch. Figure 3.5 depicts the dual-band slotted patch antenna, while Table 3.1 provides the detailed dimensions of the slotted antenna.

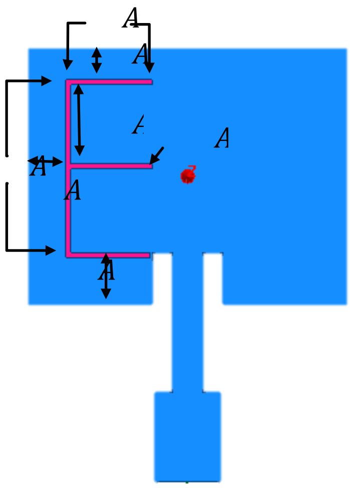

Figure 3.5 Structure of patch antenna with E shape slot.

Parameters	Values (mm)
A_t	0.304
A_d	0.8
A_r	1.75
A_e	0.05
A_z	0.56
A_s	0.454
A_b	0.775

Table 3.2 Dimensions of the patch antenna with E shape slot.

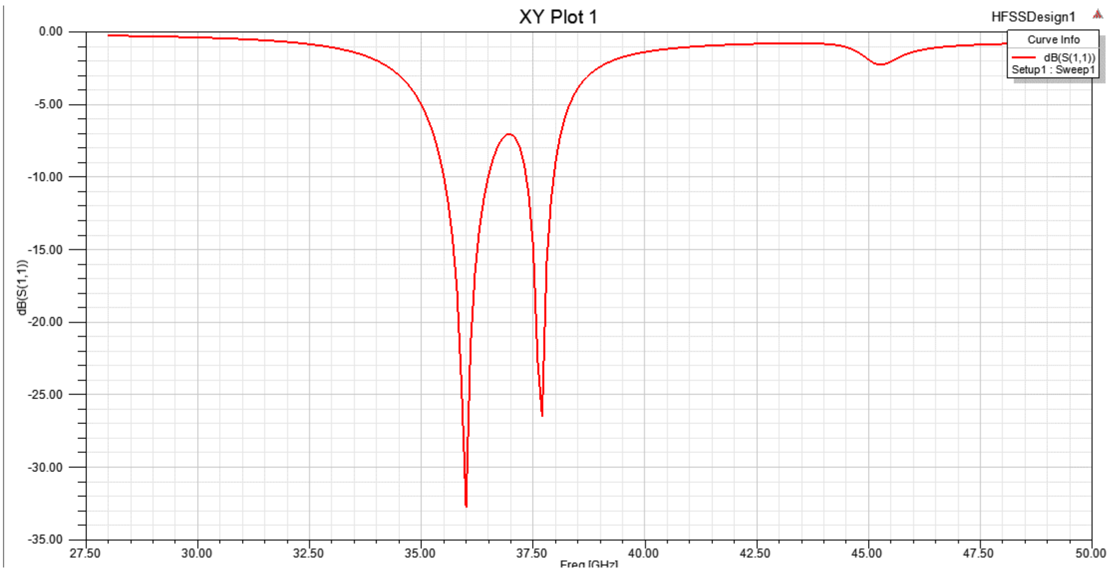

Figure 3.6 S_{11} results for patch antenna with E shape slot.

Figure 3.6 presents favourable simulated results for the patch antenna with an E slot at both resonant frequencies. The S_{11} parameter shows a magnitude of -32.7 dB at 36 GHz and -26.4 dB at 37.7 GHz, with a -10 dB bandwidth of roughly 0.8 GHz at both frequencies. Figures 3.7 and 3.8 illustrate the three-dimensional radiation patterns of this slotted antenna at 36 GHz and 37.7 GHz, respectively. The slotted patch antenna achieves a maximum gain of 10.58 dBi at 36 GHz and 13.97 dBi at 37.7 GHz.

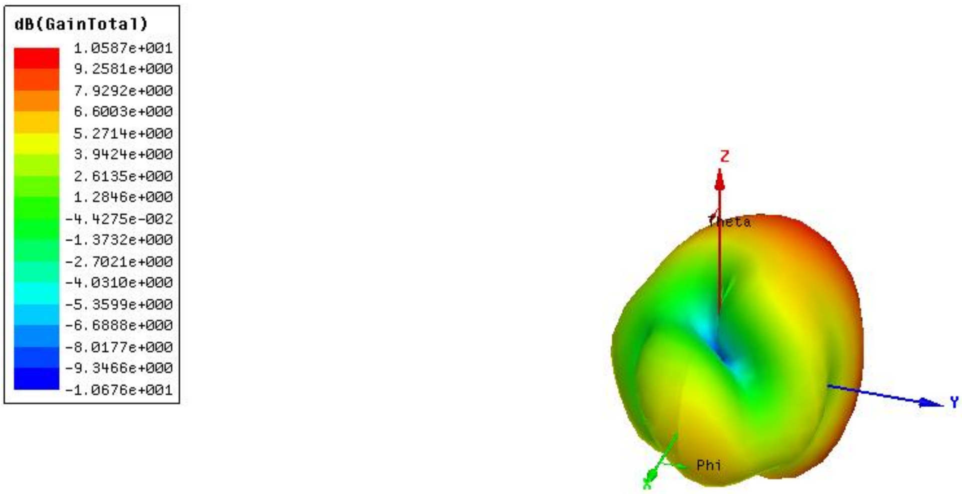

Figure 3.7 The gain of patch antenna with E slot at 36 GHz.

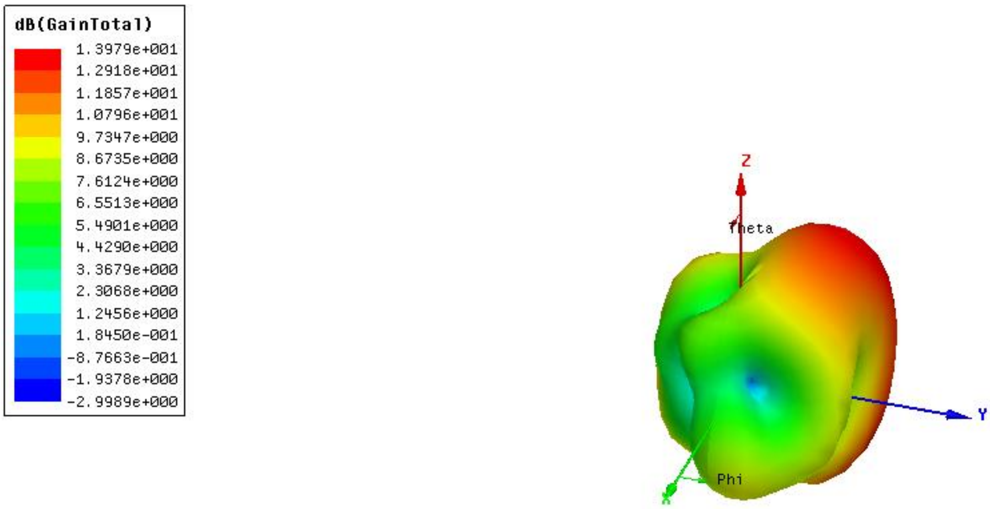

Figure 3.8 The gain of patch antenna with E slot at 37.7 GHz.

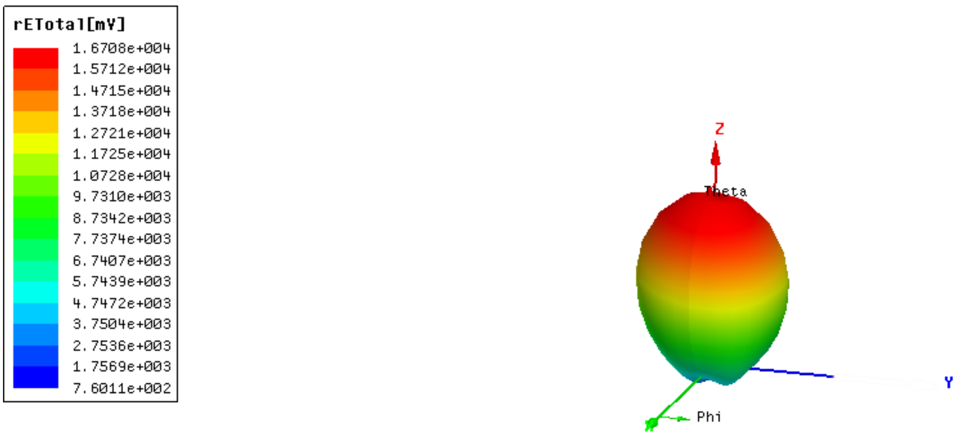

Figure 3.9 Radiation pattern of patch antenna with E slot.

3.5 Design of array antenna with two elements

Building on the E-slot patch antenna depicted in Figure 3.5, a two-element antenna array is developed to enhance the directivity and gain at the resonant frequencies of 36.5 GHz and 38.3 GHz. To achieve proper matching, a quarter-wavelength transformer is integrated into the feeding network, employing the parallel feeding method as illustrated in Figure 3.10. The dimensions of the transmission lines within the feeding network are detailed in Table 3.2.

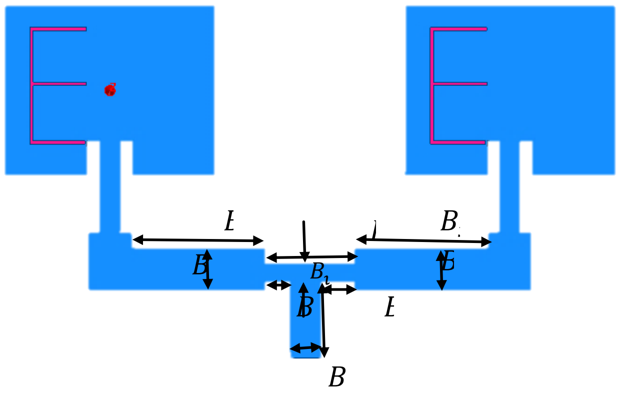

Figure 3.10 Structure of array antenna with two elements.

Parameters	Values (mm)
B_x	2.01
B_y	0.6372
B_z	0.3714
B_q	0.47
B_i	1.15
B_u	0.5014
L_f	1.38
B_v	0.25

Table 3.3 Dimensions of the transmission line between elements.

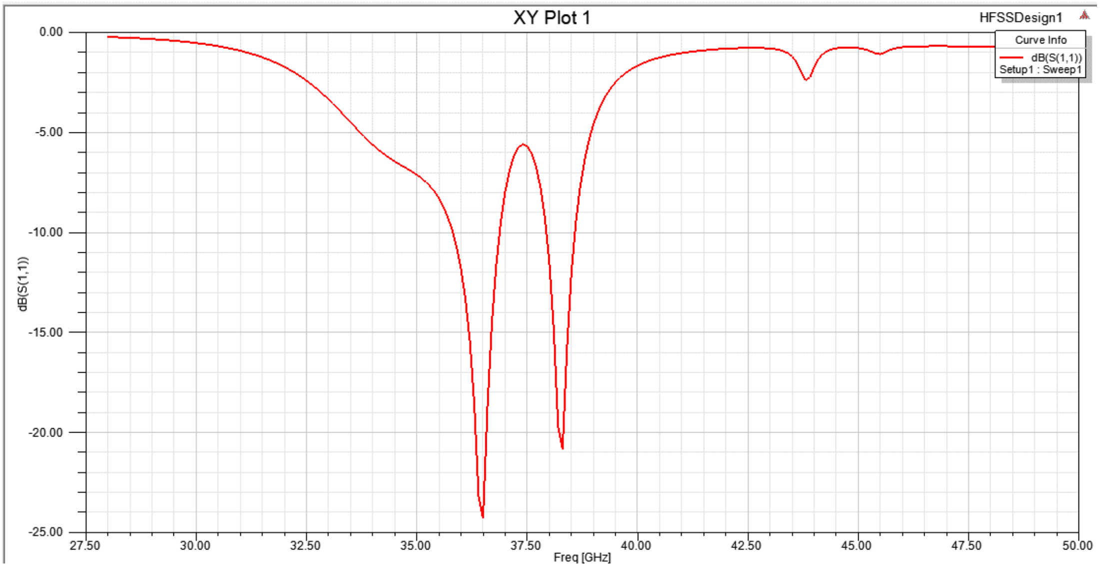

Figure 3.11 S_{11} results for array antenna with two elements.

After optimizing the dimensions of the feeding network, the simulated S_{11} results demonstrate excellent matching at the two resonant frequencies, with values of -20.09 dB at 36.5 GHz and -24.2 dB at 38.3 GHz, as shown in Figure 3.11. Additionally, the three-dimensional simulated radiation patterns at 36.5 GHz and 38.3 GHz exhibit substantial total gains of 23.45 dBi and 26.35 dBi, respectively, as illustrated in Figures 3.16 and 3.17.

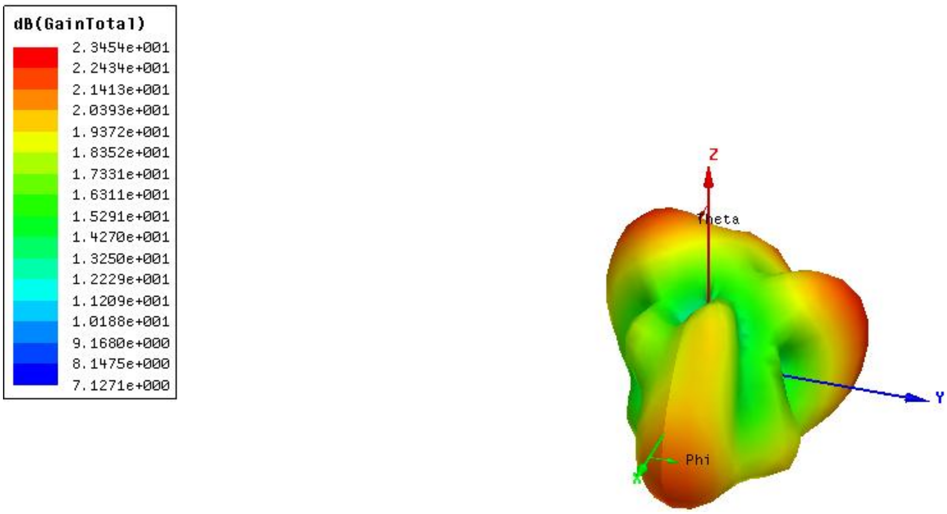

Figure 3.12 The gain of array antenna with two elements at 36.5 GHz.

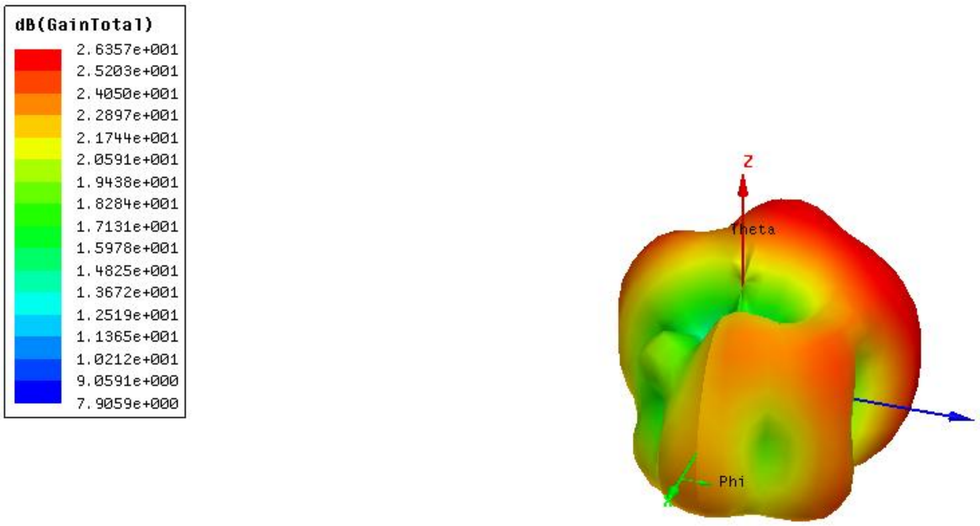

Figure 3.13 The gain of array antenna with two elements at 38.3 GHz.

Figure 3.14 Radiation pattern of the array antenna with two elements.

3.6 Design of array antenna with four elements

A four-element array antenna is designed based on the E-slotted antenna depicted in Figure 3.5. The antenna elements are fed using a parallel feeding network incorporating quarter-wavelength transformers. The configuration of the four-element array antenna is illustrated in Figure 3.15, with the distribution parameter values detailed in Table 3.3.

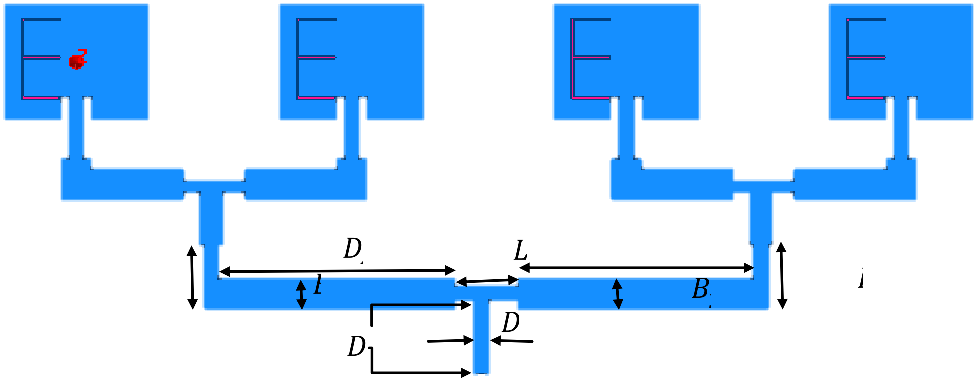

Figure 3.15 Structure of array antenna with four elements.

Parameters	Values (mm)
L_f	1.38
D_A	5.175
B_y	0.6372
D_C	1.6
D_G	0.32
D_B	5.159

Table 3.4 Dimensions of the transmission line between elements.

The S_{11} simulation result shows a good match at the resonance frequencies of -30 dB at 37.2 GHz and -15.5 dB at 38.6 GHz (Figure 3.16). The 3D simulated radiation patterns at 37.2 GHz and 38.6 GHz show good overall gains of 13.53 dBi and 15.76 dBi, respectively as shown in Figure 3.17 and Figure3.18.

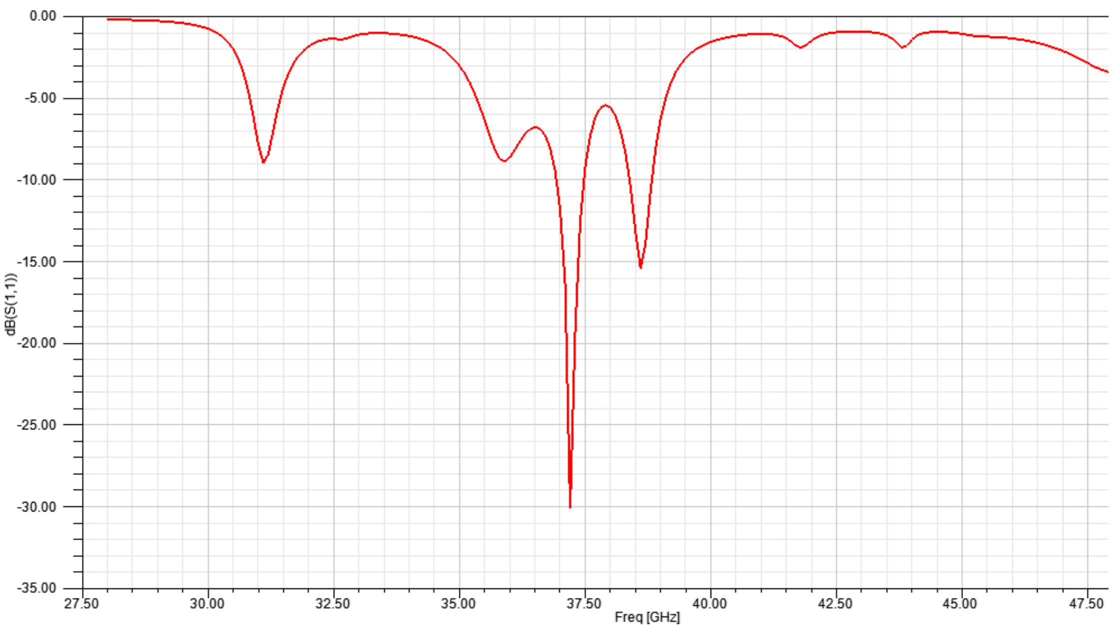

Figure 3.16 S_{11} results for array antenna with four elements.

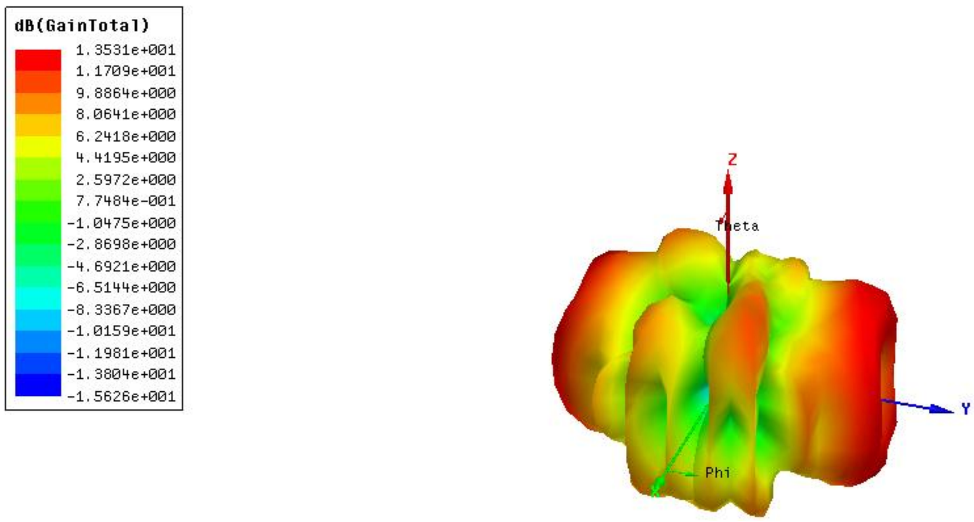

Figure 3.17 The gain of array antenna with four elements at 37.2 GHz.

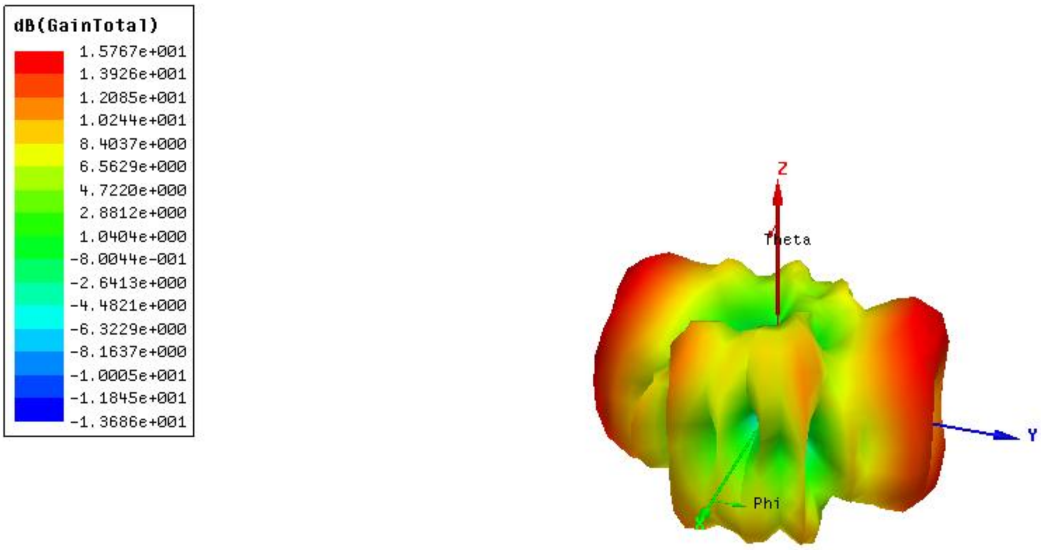

Figure 3.18 The gain of array antenna with four elements at 38.6 GHz.

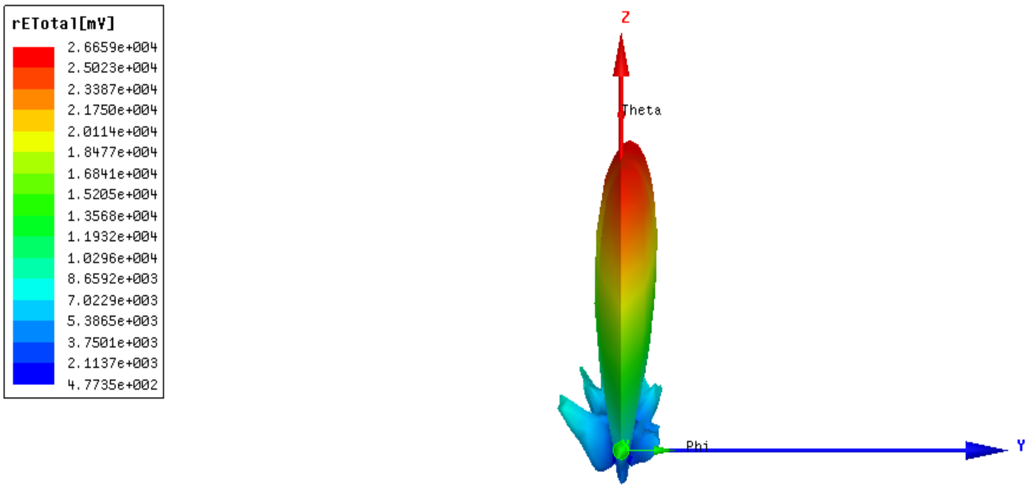

Figure 3.19 Radiation pattern of the array antenna with four elements.

3.7 Conclusion

This chapter presents a novel dual-band microstrip antenna array designed using HFSS for 5G communication systems. The dual-band functionality is achieved through an E-shaped slot in the single patch antenna, resulting in good gain performance. Recognizing the need for high gain (over 12 dBi) in 5G systems, the study employs array configurations to enhance both gain and directivity. Two-element and four-element antenna array designs are presented, successfully achieving the target gain of over 12 dBi at both resonant frequencies. This innovative design effectively meets the critical need for high-performance antennas in 5G wireless communication, paving the way for enhanced data rates and communication quality.

General Conclusion

In conclusion, this thesis has provided a comprehensive exploration of patch antenna array design for 5G applications, leveraging the capabilities of High-Frequency Structure Simulator (HFSS) and focusing on the millimeter-wave (mmWave) frequency range. Through a multidimensional approach spanning three chapters, we have delved into the intricacies of mobile communication evolution, antenna theory, and the design of 5G patch antenna arrays.

Chapter 1 set the stage by offering an insightful overview of the historical development and technological advancements in mobile communication, providing essential context for the challenges and opportunities presented by the 5G era. In chapter 2, we deepened our understanding of antenna theory, covering fundamental concepts such as radiation patterns, gain, polarization, and impedance matching, laying a solid theoretical foundation for the subsequent chapters.

The heart of this thesis lies in chapter 3, where we embarked on a detailed exploration of patch antenna array design for 5G networks. Leveraging the capabilities of HFSS, we investigated various design methodologies, optimization techniques, and simulation tools to develop efficient and high-performing antenna arrays operating in the mmWave frequency range. We presented a novel dual-band microstrip antenna array designed using HFSS for 5G communication systems. By incorporating an E-shaped slot in the simple patch antenna, the design achieved dual-band functionality with good gain performance (36 GHz and 37.7 GHz exhibit substantial total gains of 10.58 dBi and 13.97 dBi, respectively). To meet the high gain requirements (over 12 dBi) essential for 5G systems, array configurations were employed to enhance both gain and directivity. Two-element and four-element antenna array designs were successfully developed, achieving the target gain at both resonant frequencies. For antenna array with two elements, the frequencies 36.5 GHz and 38.3 GHz exhibit substantial total gains of 23.45 dBi and 26.35 dBi, respectively. The antenna array with four elements presents two resonate frequencies 37.2 GHz and 38.6 GHz which show good gains of 13.53 dBi and 15.76 dBi, respectively. This innovative design addresses the critical need for high-performance antennas in 5G wireless communication, paving the way for enhanced data rates and communication quality.

By integrating the insights obtained from chapters 1 and 2 with the practical expertise acquired in chapter 3, this thesis significantly contributes to the progression of patch antenna array design for 5G networks. It emerges as an invaluable asset for researchers, engineers, and practitioners aiming to innovate in the realm of antenna technology, thereby facilitating the full exploitation of 5G communications capabilities in the mmWave era.

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