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Conception of a Patch Antenna for 5G Applications

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Dedication

In the light of my life, my dearest parents, all the words in the world cannot express the deep gratitude and immense love I have for you. It is the sacrifices you have never ceased to make for my education and well-being that have enabled me to live this day.

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To my dear mother.

To my aunts and uncles.

To my cousins.

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List of Abbreviations

4G	the fourth generation
5G	the fifth generation
5GC	5G core network
AMF	Access and Mobility Function
AUSF	Authentication Server Function
BSF	Binding Support Function
CN	Core Network
CPF	control plane function
C-RAN	Cloud RAN
CUs	central units
DRA	Diameter Routing Agent
D-RAN	distributed RAN
DTH	direct-to-home
DUs	distributed units
eMBB	Enhanced mobile broadband
HFSS	High Frequency Structure Simulator
HSS	Home Subscriber Server
IoT	Internet of Things
ISL	Intersatellite links
LTE	Long Term Evolution
MEC	Mobile edge computing
MIMO	massive multiple-input multiple-output
mMTC	Massive machine-type communications
mmWave	millimeter-wave
NEF	network exposure function
NFC	NF Service Consumers

NFP	NF Service Producer
NRF	Network Repository Function
NSSF	Network Slicing Selection Function
NWDAF	Network Data Analytics Function
PCB	Printed circuit board
PCF	Policy Control Function
PCF	Policy Control Function
QoS	quality of service
RAN	Radio Access Network
RFID	Radio-frequency identification
SBA	service-based architecture
SBA	service-based architecture
SCP	Service Communication Proxy
SIW	Substrate Integrated Waveguide
SMF	session management function
UDM	Unified Data Management
UDR	User Data Repository
UDR	User Data Repository
UE	User Equipment
UPF	user plane function
URLLC	Ultra-reliable low-latency communications
Wi-Fi	wireless fidelity

General Introduction

5G is the fifth generation of mobile networks, which represents a significant advancement in mobile communication technology. It offers faster data rates, lower latency, and a wider range of use cases and applications compared to previous generations of mobile networks.

With 5G, users can experience faster download and upload speeds, better video quality, and improved network reliability. This technology also enables new applications such as IoT, autonomous vehicles, virtual reality, and more.

5G networks use a combination of different technologies such as millimeter waves, massive MIMO, beamforming, and full-duplex to achieve faster speeds and lower latency. The architecture of 5G networks is also more complex compared to previous generations, with a new core network and different types of access networks such as small cells and new generation antennas.

Although there are some concerns around the potential health effects of 5G radiation and the cost of upgrading to 5G networks, the benefits of 5G technology are expected to outweigh these concerns in the long run.

5G represents a major advancement in mobile communication technology, paving the way for a new era of connected devices and applications that will transform the way we live, work, and communicate.

Chapter 1

Generality of fifth generation networks

1.1 Introduction

5G is the latest generation of wireless communication technology that is designed to revolutionize the way we connect to the internet and communicate with each other. It is a significant upgrade over its predecessor, 4G LTE, and is expected to deliver lightning-fast speeds, low latency, and massive capacity.

5G promises to be a game-changer in many ways. It will enable a whole host of new applications and services that were previously impossible, such as remote surgery, self-driving cars, and smart cities. It will also improve the quality of internet connectivity, making it more reliable and accessible to a broader range of people.

1.2 Principle and architecture of the fifth generation networks

FIGURE 1.1. Techniques used in 5G technology

1.2.1 5G networks principle

5G is based on two main technologies, namely millimeter-wave (mmWave) radio and massive multiple-input multiple-output (MIMO) technology. Millimeter-wave radio allows for wider bandwidth, meaning faster data speeds, but has a shorter range. Massive MIMO allows for better network capacity by increasing the number of antennas for faster and more reliable data transmission.

1.2.1.1 Millimeter waves

Millimeter waves (mmWave) are electromagnetic waves with wavelengths between 1 and 10 millimeters. They are a type of high-frequency radio waves that fall in the spectrum between microwaves and infrared waves.

In telecommunications, mmWave frequencies are used for high-speed data transmission in wireless communication systems such as 5G networks. These frequencies are capable of carrying large amounts of data, enabling faster data rates and more reliable connectivity.

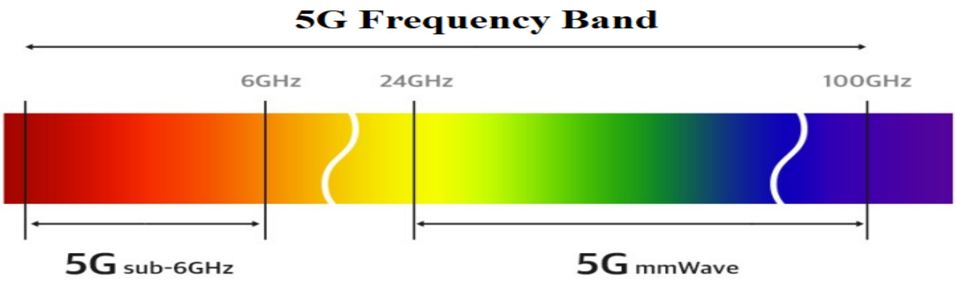


FIGURE 1.2. Millimeter waves

However, mmWave signals have a shorter range and can be blocked by obstacles such as buildings and trees, which can cause signal attenuation and degradation. To overcome this, mmWave systems use beamforming technology to focus the signal in a specific direction and increase signal strength, allowing for more reliable transmission over longer distances.

MmWave technology has the potential to revolutionize wireless communications and enable new applications such as augmented reality, virtual reality, and autonomous vehicles.

1.2.2 Microwaves

Micro waves are electromagnetic waves with wavelengths ranging from about 1 millimeter to 1 meter. They are used in a variety of applications such as telecommunications, radar, and satellite communication.

In telecommunications, microwave frequencies are commonly used for wireless communication systems such as cellular networks and Wi-Fi. These frequencies are capable of carrying large amounts of data and can transmit signals over longer distances than millimeter waves.

Microwave technology is also used in radar systems for detecting and tracking objects such as aircraft, ships, and weather patterns. In addition, microwave frequencies are used in satellite communication to transmit signals between ground stations and satellites in orbit.

However, like all electromagnetic waves, microwaves can be affected by interference and attenuation caused by obstacles such as buildings and trees. To overcome this, microwave systems often use techniques such as frequency hopping, spread spectrum, and diversity reception to improve signal quality and reliability.

Microwave technology plays a critical role in modern telecommunications and has enabled many of the wireless communication systems and applications that we rely on today.

1.2.3 Massive MIMO

Massive multiple-input multiple-output (MIMO) is a wireless communication technology that uses multiple antennas at the transmitter and receiver to improve the performance and efficiency of wireless communication systems.

In traditional MIMO systems, a small number of antennas are used to transmit and receive data. In contrast, massive MIMO uses a large number of antennas, typically in the range of tens or hundreds, to transmit and receive data simultaneously.

The key advantage of massive MIMO is that it improves the spectral efficiency of wireless communication systems, which means that it allows more data to be transmitted over a given bandwidth. This is achieved by using advanced signal processing techniques to separate signals transmitted by different antennas, which reduces interference and allows for more efficient use of the available spectrum.

In addition to improving spectral efficiency, massive MIMO also improves the coverage and reliability of wireless communication systems. This is because the use of multiple antennas allows for better signal diversity and spatial multiplexing, which can improve the signal-to-noise ratio and reduce the effects of fading.

Massive MIMO is a key technology in 5G networks and is expected to play an important role in the development of future wireless communication systems. Its ability to improve spectral efficiency, coverage, and reliability makes it well-suited for applications such as virtual reality, augmented reality, and the Internet of Things (IoT).

1.2.4 Beamforming

Beamforming is a wireless communication technique that allows the transmission and reception of signals in a specific direction or pattern, instead of broadcasting signals in all directions. It uses multiple antennas to transmit and receive signals in a focused beam, which can improve the quality and reliability of wireless communication systems.

In beamforming, the antennas are coordinated to form a beam that is aimed at the intended receiver. This can improve the signal strength and reduce interference from other sources. The beamforming algorithm dynamically adjusts the phase and amplitude of the signals transmitted by each antenna to optimize the direction of the beam and improve signal quality.

Beamforming is used in a variety of wireless communication systems, including cellular networks, Wi-Fi, and satellite communication. It is particularly useful in 5G networks, where it is used with millimeter wave frequencies to overcome the limitations of short range and signal blockage.

There are two main types of beamforming : analog beamforming and digital beamforming. Analog beamforming uses phase shifters to adjust the signals transmitted by the antennas, while digital beamforming uses digital signal processing techniques to adjust the signals after they have been transmitted.

Beamforming has many advantages over traditional wireless communication techniques. It can improve signal quality, increase data rates, and reduce interference. As a result, it is expected to play an important role in the development of future wireless communication systems.

1.2.5 Full-Duplex

Full-duplex is a wireless communication technology that allows for simultaneous transmission and reception of signals on the same frequency band. In traditional wireless communication systems, transmission and reception occur on separate frequency bands, which can limit the data rates and capacity of the system.

In full-duplex systems, advanced signal processing techniques are used to separate the transmitted signal from the received signal, allowing for simultaneous transmission and reception on the same frequency band. This can significantly increase the data rates and capacity of the system, as well as reduce latency and improve reliability.

Full-duplex technology is used in a variety of wireless communication systems, including cellular networks, Wi-Fi, and satellite communication. It is particularly useful in applications where high data rates and low latency are required, such as video conferencing, online gaming, and virtual reality.

However, full-duplex technology also presents some challenges. One of the main challenges is the need for advanced signal processing techniques to separate the transmitted and received signals, which can be computationally intensive and require significant processing power. In addition, full-duplex systems can be susceptible to self-interference, which occurs when the transmitted signal interferes with the received signal.

Despite these challenges, full-duplex technology has the potential to revolutionize wireless communication systems and enable new applications that require high data rates and low latency.

1.3 5G networks architecture

5G is designed as a service-based architecture (SBA). This means that the various functions of the network are decomposed into services that can be called independently of each other. This service-based architecture offers greater flexibility and scalability to meet the demands of future services [1].

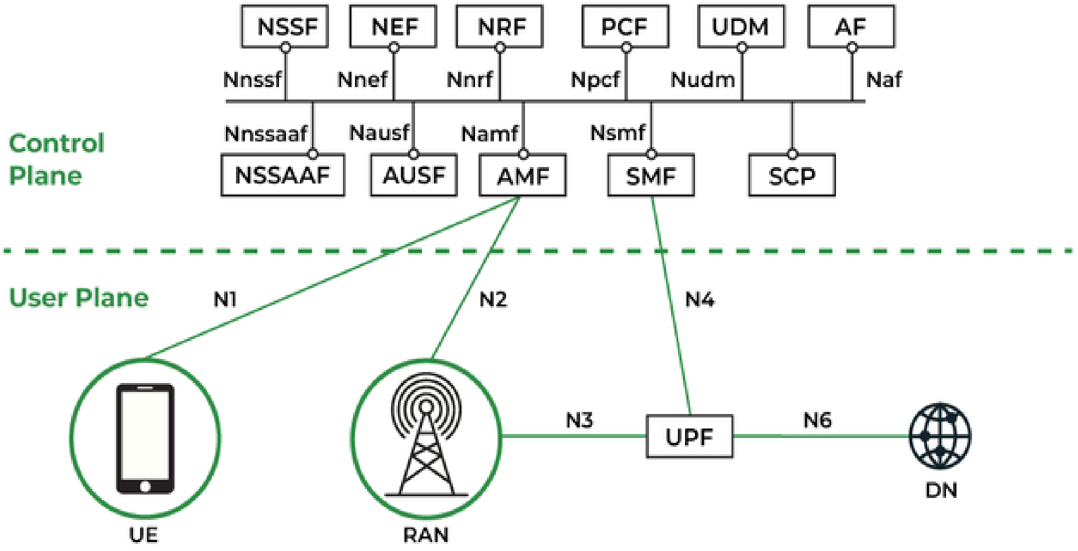


FIGURE 1.3. 5G Network Architecture

In service-based or reference point representation, the interaction between network operations is depicted. Service-based is how the 5G architecture is described.

One form of capability made available by an NF (NF Service Producer) to other authorized NF (NF Service Consumers) through a service-based interface is a network function service. One form of capability made available by an NF (NF Service Producer) to other authorized NF (NF Service Consumers) through a service-based interface is a network function service.

Network functions may expose one or more services, which means that a producer may give one or more consumers access to a service-based interface. It consists of a number of services, each of which is composed of a number of procedures in the manner of NNRF MANAGEMENT, NBSF MANAGEMENT [2].

The 5G network architecture consists of three main components : the user equipment (UE), the radio access network (RAN), and the core network (CN).

The user equipment includes devices such as smartphones, tablets, and other wireless devices that connect to the 5G network. These devices use the 5G radio access network to communicate with the core network and other devices on the network [1].

The radio access network includes base stations and other equipment that transmit and receive signals to and from the user equipment. The 5G RAN uses advanced technologies such as massive MIMO and beamforming to improve the spectral efficiency and coverage of the network. It also supports multiple frequency bands, including both sub-6 GHz and millimeter wave frequencies.

The core network provides the underlying services and functions that enable the 5G network to operate. It includes components such as the mobile edge computing (MEC), network slicing, and virtualization. These technologies enable the 5G network to provide a variety of services, including :

Enhanced mobile broadband (eMBB) : This service provides high-speed mobile data connections that can support applications such as streaming video, online gaming, and virtual reality [2].

Ultra-reliable low-latency communications (URLLC) : This service provides low-latency, high-reliability connections that are suitable for applications such as industrial automation, autonomous vehicles, and remote surgery [1].

Massive machine-type communications (mMTC) : This service provides connectivity for a large number of devices, such as sensors and other IoT devices, that require low data rates and low power consumption [2].

Network slicing : This technology allows the 5G network to be divided into virtual networks, or slices, that can be customized for specific applications or services.

Mobile edge computing (MEC) : This technology enables applications and services to be run on servers located at the edge of the network, closer to the user equipment. This can reduce latency and improve the performance of applications that require real-time processing.

The 5G network architecture and its services are designed to provide high-speed, low-latency connectivity for a wide range of applications and devices. With its advanced technologies and capabilities, 5G is expected to play a critical role in the development of new applications and services in areas such as healthcare, transportation, and smart cities.

1.3.1 Functions of 5G network

1.3.1.1 NRF(Network Repository Function)

All of the 5G network functions (NFs) in the operator's network are stored centrally in the Network Repository Function (NRF). The NRF provides a standards-based API that enables 5G NFs to register and find one another. A crucial element needed to execute the new service-based architecture (SBA) in the 5G core is NRF [3].

1.3.1.2 PCF (Policy Control Function)

Policy Control Function makes it simple to develop and implement policies in a 5G network. PCF will help you monetize and reap the rewards of 5G because it was created and designed using cloud-native principles to address the demands of 5G services [3].

1.3.1.3 BSF (Binding Support Function)

The Session Binding Function on the Diameter Routing Agent (DRA) used in 4G is comparable to the 5G Binding Support Function (BSF). When numerous Policy Control Function (PCF) systems are installed in the network, it becomes a necessary necessity [2].

1.3.1.4 SCP (Service Communication Proxy)

By granting routing control, resiliency, and observability to the core network, Service Communication Proxy (SCP) enable operators to securely and effectively operate their 5G network. To address many of the issues brought on by the new service-based architecture

(SBA) in the 5G core, SCP makes advantage of IT service mesh (ISTIO) and adds crucial capabilities to make it 5G-aware [3].

1.3.1.5 NSSF (Network Slicing Selection Function)

In the 5G environment, where a variety of services are offered, the NSSF (Network Slicing Selection Function) system is a solution to choose the best network slice available for the service requested by the user [4].

1.3.1.6 UDM (Unified Data Management) & UDR (User Data Repository)

UDM is cloud-native and created for 5G, similar to Home Subscriber Server (HSS) in LTE. It is in charge of creating the credentials needed for authentication, granting access depending on user subscription, and sending those credentials to the other network functions. It retrieves the credentials from the User Data Repository (UDR). Different key 5G features are supported by the UDM network function. In order to complete the authentication process, it creates authentication credentials. Based on user subscriptions, it approves network access and roaming [4].

1.3.1.7 AUSF (Authentication Server Function)

5G authentication and Key Agreement method 5G AKA are carried out via the authentication server function. In order to manage hidden or privacy-protected subscription identifiers, AUSF also provides additional functionality. During the registration process, AMF(Access and Mobility Function) is in charge of choosing the proper Authentication Server Function (AUSF) [4].

1.3.1.8 NWDAF (Network Data Analytics Function)

The 5G Network Data Analytics Function (NWDAF) is intended to improve the end-user experience by streamlining the production and consumption of key network data as well as generating insights and taking appropriate action. By expediting the production and consumption of core network data, creating insights, and acting on these insights, NWDAF is intended to address market fragmentation and proprietary solutions in the field of network analytics [4].

1.3.2 5G Core Network

The 5G core network (5GC) is the backbone of the 5G network architecture that provides the underlying services and functions required to support the 5G radio access network (RAN) and the user equipment (UE). It is a completely new core network architecture that is designed to be flexible, scalable, and modular, enabling operators to deploy new services and applications quickly and efficiently [5].

The 5GC is built around three key functions : the user plane function (UPF), the control plane function (CPF), and the network exposure function (NEF).

The UPF is responsible for processing and routing user data between the UE and the applications running on the network. It is designed to support high bandwidth, low latency, and efficient use of network resources, making it possible to deliver high-speed mobile broadband services, such as video streaming and online gaming, over the 5G network [5].

The CPF is responsible for managing the signaling and control functions that enable the UE to connect to the 5G network, authenticate the user, and establish the session between the UE and the application. It also supports features such as network slicing and quality of service (QoS) management, which enable operators to customize the network for specific use cases and applications [6].

The NEF is responsible for providing access to the 5G network services and functions through a set of standardized APIs. This allows third-party developers and service providers to easily integrate their applications and services with the 5G network, enabling a wide range of new use cases and applications [5].

Other key functions of the 5GC include the session management function (SMF), which manages the session between the UE and the network, and the network repository function (NRF), which provides information about the network topology and available services [5].

The 5GC is designed to support a wide range of use cases and applications, including enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). With its flexible, scalable, and modular architecture, the 5GC is expected to play a critical role in enabling the development of new 5G services and applications in areas such as healthcare, transportation, and smart cities [5].

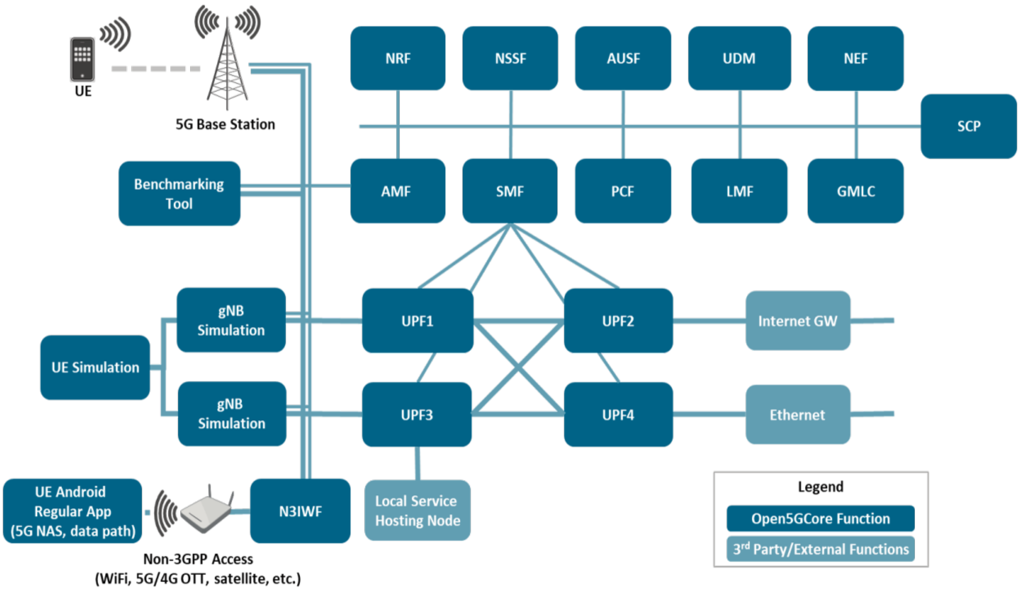


FIGURE 1.4. 5G Core Network

1.3.2.1 Radio access network

The radio access network (RAN) is an important component of mobile networks, including 5G. It is responsible for establishing the wireless connection between mobile devices and the core network, which manages network traffic and other network functions.

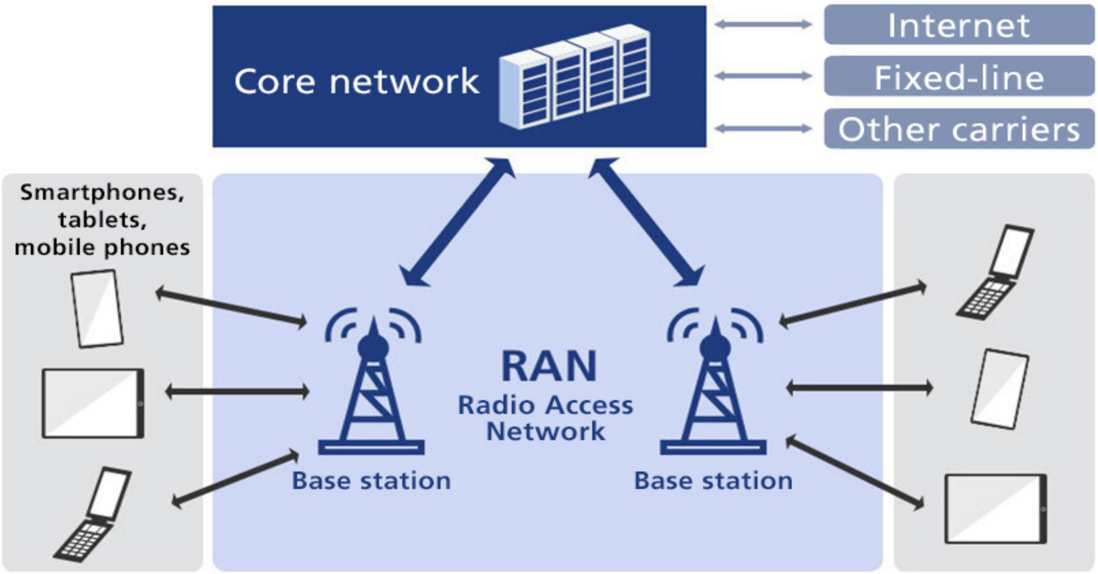


FIGURE 1.5. The radio access network

In 5G, the RAN is composed of small cells and new generation antennas, which are designed to provide faster speeds and lower latency compared to previous generations.

These technologies include [7] :

Millimeter waves : 5G uses high frequency bands in the millimeter wave range (above 24 GHz) to provide faster speeds and more bandwidth compared to previous generations [1].

Massive MIMO : This technology uses multiple antennas at both the transmitter and receiver to improve network performance and reduce interference.

Beamforming : This technology allows the network to focus the radio signal in a specific direction, increasing the signal strength and reducing interference.

Full-duplex : This technology enables simultaneous transmission and reception on the same frequency band, improving network capacity and reducing latency.

In addition to these technologies, the 5G RAN also includes new network architecture, such as distributed RAN (D-RAN) and Cloud RAN (C-RAN), which enable more flexible and scalable network deployment.

The 5G RAN is a key component of the 5G network architecture, enabling faster speeds, lower latency, and a wider range of use cases and applications.

1.3.2.2 Distributed RAN (D-RAN)

Distributed RAN (D-RAN) is a network architecture used in 5G networks that distributes the baseband processing among multiple sites, instead of centralizing it in a single location as in Cloud RAN (C-RAN). This architecture is designed to improve network performance, reduce latency, and provide better coverage.

In a D-RAN architecture, the baseband processing is distributed among multiple sites, called central units (CUs) and distributed units (DUs), instead of being centralized in a single location. The CUs are located at a central site and are responsible for higher-level processing and coordination, while the DUs are located closer to the radio units and are responsible for lower-level processing.

The D-RAN architecture enables better coordination between the DUs, reducing latency and improving network performance. It also allows for more flexible and modular network deployment, as the DUs can be deployed in different locations and can be easily scaled based on network demands.

D-RAN architecture also enables network slicing, which allows multiple virtual networks to run on the same physical infrastructure, each with its own set of resources and network capabilities. This enables better resource utilization and more efficient network management.

D-RAN is a key component of the 5G network architecture, enabling better network performance, reduced latency, and improved coverage, while providing more flexible and scalable network deployment options.

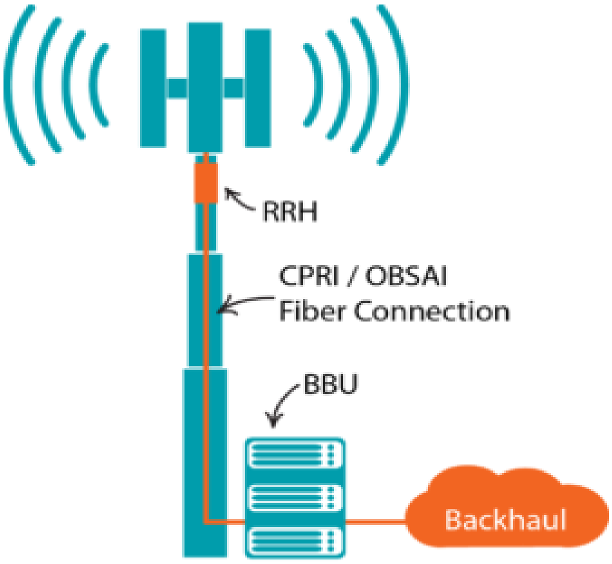


Figure 1 - D-RAN Base Transceiver Station

FIGURE 1.6. Distributed RAN (D-RAN)

1.3.2.3 Backhaul

Backhaul refers to the network infrastructure used to connect the radio access network (RAN) to the core network in a cellular network architecture. In a 5G network, backhaul plays a critical role in providing high-speed and reliable connectivity between the base stations and the core network, enabling seamless delivery of services to end-users.

The backhaul network typically consists of high-capacity fiber optic cables or microwave links, which connect the base stations to the core network. The backhaul network must be designed to support the high bandwidth requirements of 5G networks, which can be up to 10 times higher than those of 4G networks.

To meet the high-bandwidth requirements of 5G networks, some operators are exploring new backhaul technologies such as millimeter-wave (mmWave) wireless links, which can provide high-speed connectivity over short distances. Another option is to use satellite backhaul, which can provide connectivity to remote and rural areas where traditional fiber optic backhaul may not be available.

backhaul is a critical component of 5G network architecture, providing the necessary high-speed and reliable connectivity to support the delivery of 5G services to end-users.

1.3.2.4 Cloud RAN (C-RAN)

Cloud RAN (C-RAN) is a network architecture used in 5G networks that centralizes baseband processing in the cloud. This architecture is designed to improve network efficiency and scalability while reducing costs and power consumption.

In a C-RAN architecture, the baseband processing units (BBUs) are centralized in a data center or cloud-based facility, while the remote radio units (RRUs) are deployed at the network edge, closer to the end-user devices. The BBUs and RRUs are connected via high-speed fiber optic cables or wireless links, using protocols such as Ethernet, Common Public Radio Interface (CPRI), or Open Radio Access Network (O-RAN).

The centralized baseband processing in a C-RAN architecture allows for better coordination between RRUs, improving network efficiency and reducing interference. It also enables more flexible and scalable network deployment, as the BBUs can be shared among multiple RRUs, reducing the need for redundant equipment.

C-RAN architecture also enables network virtualization, allowing multiple virtual networks to run on the same physical infrastructure, improving resource utilization and reducing costs. Additionally, C-RAN can support software-defined networking (SDN) and network functions virtualization (NFV), enabling more agile and programmable network management.

C-RAN is a key component of the 5G network architecture, enabling more efficient, flexible, and scalable network deployment while reducing costs and power consumption.

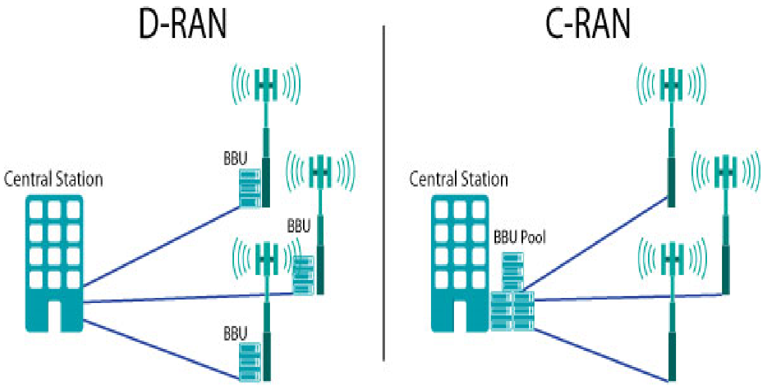


FIGURE 1.7. Cloud RAN (C-RAN)

1.3.2.5 User equipment (UE)

User Equipment (UE) is the technical term used to refer to the end-user devices, such as smartphones, tablets, laptops, and IoT devices, that are used to access cellular networks. In the context of 5G, UE refers specifically to devices that are compatible with 5G network technology.

1.4 Comparison between different generations

Here are some key differences between the different generations of mobile networks [8] :

Data rates : The data rates of each generation of mobile networks have increased significantly with each new generation. For example, the maximum theoretical data rate for 1G was 2.4 kbps, while the maximum theoretical data rate for 5G is up to 20 Gbps.

Latency : The latency or delay between the user's device and the network has decreased significantly with each new generation. For example, the average latency for 4G is around 30-40 milliseconds, while the average latency for 5G is expected to be around 1-10 milliseconds.

Network architecture : The network architecture of each generation has changed significantly. For example, 1G was an analog system with no real network architecture, while 2G was the first digital system with a simple network architecture. 3G introduced a more complex network architecture, and 4G introduced the concept of an all-IP network.

Spectral efficiency : The spectral efficiency of each generation has increased significantly. This means that more data can be transmitted using the same amount of spectrum. For example, the spectral efficiency of 1G was around 0.1 bps/Hz, while the spectral efficiency of 5G is expected to be around 30 bps/Hz.

Number of connected devices : Each generation has been able to support an increasing number of connected devices. For example, 2G was primarily designed for voice and could support a limited number of connected devices, while 5G is designed to support up to 1 million connected devices per square kilometer.

Use cases and applications : Each generation has enabled new use cases and applications. For example, 2G enabled basic voice and text messaging, while 3G enabled mobile data and basic internet browsing. 4G enabled high-speed mobile broadband, and 5G is expected to enable a wide range of new use cases and applications, including IoT, autonomous vehicles, and virtual reality.

Each generation of mobile networks has brought significant improvements in terms of data rates, latency, network architecture, spectral efficiency, number of connected devices, and use cases and applications. 5G is expected to bring the most significant improvements yet, enabling a new level of connectivity that can support a wide range of new use cases and applications.

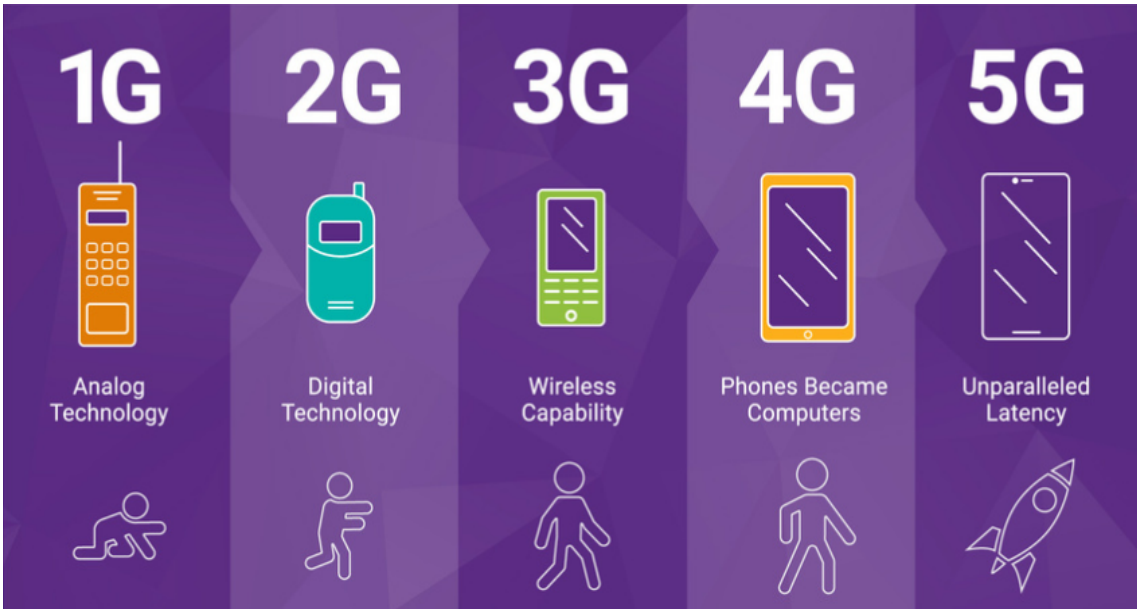


FIGURE 1.8. Comparison between different generations

1.5 5G around the world

5G networks are being deployed around the world, although the level of deployment and adoption varies by country and region. Here are some examples of 5G deployment around the world [9] :

United States : 5G networks are being deployed by major carriers such as Verizon, AT&T, and T-Mobile. Some cities have already been fully covered by 5G, while others are still being deployed.

China : China is one of the countries with the largest 5G deployment in the world. Major carriers such as China Mobile, China Unicom, and China Telecom are deploying 5G networks across the country.

South Korea : South Korea was one of the first countries to launch 5G networks. All three major carriers in South Korea (SK Telecom, KT, and LG Uplus) have deployed 5G networks across the country.

United Kingdom : Major carriers such as EE, Vodafone, and O2 are deploying 5G networks across the UK. Some cities have already been fully covered by 5G, while others are still being deployed.

Japan : Major carriers such as NTT Docomo, SoftBank, and KDDI are deploying 5G networks across Japan. Some cities have already been fully covered by 5G, while others are still being deployed.

Australia : Major carriers such as Telstra, Optus, and Vodafone are deploying 5G networks across Australia. Some cities have already been fully covered by 5G, while others are still being deployed.

Europe : 5G networks are being deployed across many countries in Europe, including Germany, France, Italy, Spain, and the Netherlands. Major carriers such as Deutsche Telekom, Orange, Vodafone, and Telefonica are leading the deployment efforts.

Algeria : The Algerian government aims to ensure the launch of 5G mobile networks ’soon’ and is currently working on freeing up and optimizing the requisite radio frequency spectrum, telecoms minister Karim Bibi Triki announced in a presentation mars 2023 , Agency Ecofin reported.

5G networks are being deployed around the world, although the level of deployment and adoption varies by country and region. Many countries are still in the early stages of 5G deployment, while others have already achieved significant coverage.

1.6 Broadcast of the 5G networks

To broadcast a 5G network, you will need the following hardware [10] :

5G Base Station : This is the hardware that generates the 5G radio waves and transmits them wirelessly. Base stations can come in various forms, including macro cells, small cells, and distributed antenna systems.

Antennas : Antennas are used to transmit and receive the 5G radio waves generated by the base station. There are several types of antennas used in 5G networks, including directional antennas, omnidirectional antennas, and MIMO antennas.

Routers/Modems : Routers and modems are used to connect end-user devices to the 5G network. They can come in various forms, including home routers, mobile hotspots, and 5G-enabled smartphones and tablets.

Network Equipment : This includes hardware such as switches, servers, and storage devices, which are used to manage the flow of data across the 5G network.

Spectrum : To operate a 5G network, you will need access to a portion of the radio frequency spectrum. This can be obtained through licensing agreements with regulatory authorities.

Anyway broadcasting a 5G network requires a combination of hardware components, including base stations , routers/modems, network equipment, and access to the radio frequency spectrum. And a lot others that we are not going to talk about today.

In our research we are going to focus on the antennas , specifically the patch antennas and the SIW technology (Substrate-integrated waveguide).

1.7 Conclusion

The next generation of cellular network technology, 5G, offers faster data speeds, lower latency, and better connectivity. It comprises the Radio Access Network, Core Network, and User Equipment, all of which contribute to its capabilities. The Radio Access

Network consists of various components, including antennas, which play a crucial role in broadcasting the signal. In 5G networks, millimeter waves and massive MIMO antennas are used for beam forming, which enhances signal strength and reduces interference.

5G UEs are power-efficient, support multiple frequency bands, and are designed to support high-speed and low-latency. Although 5G is being rolled out worldwide, there are concerns about security, privacy, and health effects. However, 5G has the potential to drive innovation and enable new applications and services, including smart cities, autonomous vehicles, and virtual reality.

Chapter 2

Printed antennas and SIW technology

2.1 Introduction

Antennas are crucial devices used for transmitting and receiving electromagnetic waves in various electronic systems, including communication, radar, satellite, and wireless networks. They come in different shapes and sizes, with their performance determined by design, frequency range, and application. This article provides an overview of commonly used antennas, such as dipole, Yagi, patch, horn, parabolic, helical, and log-periodic antennas.

2.2 Antenna

Antennas are devices that are used to transmit and receive electromagnetic waves. They are an essential component of various electronic systems, including communication systems, radar systems, satellite systems, and wireless networks. Antennas come in various shapes and sizes, and their performance depends on their design, frequency range, and application.

2.2.1 Types of Antennas

There are many types of antennas, each with its own characteristics and advantages. In this introduction, we will provide an overview of the most commonly used types of antennas.

Dipole Antennas : Dipole antennas are the simplest and most widely used type of antenna. They consist of two conductive elements that are parallel to each other and separated by a small gap. The elements can be either straight or bent into a V shape. Dipole antennas are commonly used in radio and television broadcasting, as well as in wireless communication systems [11].

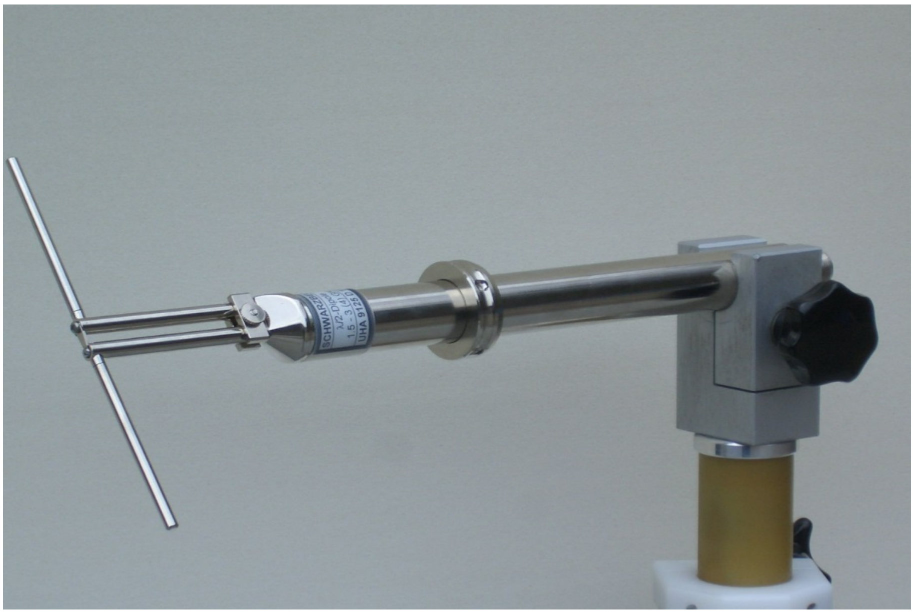


FIGURE 2.1. Dipole antenna

Yagi Antennas : Yagi antennas, also known as directional antennas, are designed to focus the radiation in a specific direction. They consist of a series of dipole elements arranged in a linear array, with one element acting as the driven element and the others acting as parasitic elements. Yagi antennas are commonly used in television broadcasting, as well as in wireless communication systems, such as cellular networks [12].

FIGURE 2.2. Yagi Antenna

Patch Antennas : Patch antennas, also known as microstrip antennas, are a type of planar antenna that are commonly used in wireless communication systems. They consist of a thin metallic patch that is printed on a dielectric substrate. Patch antennas are low profile, lightweight, and easy to integrate into electronic circuits, making them ideal for use in mobile devices.

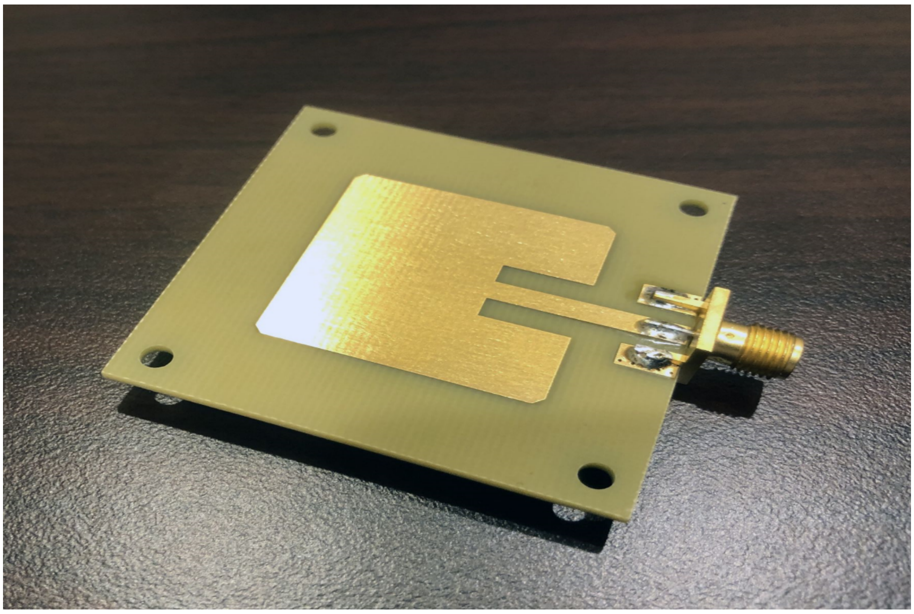


FIGURE 2.3. Patch Antenna

Horn Antennas : Horn antennas are a type of directional antenna that are designed to have a wide bandwidth and a high gain. They consist of a flared metal horn that is fed by a waveguide. Horn antennas are commonly used in radar systems, as well as in satellite communication systems [11].

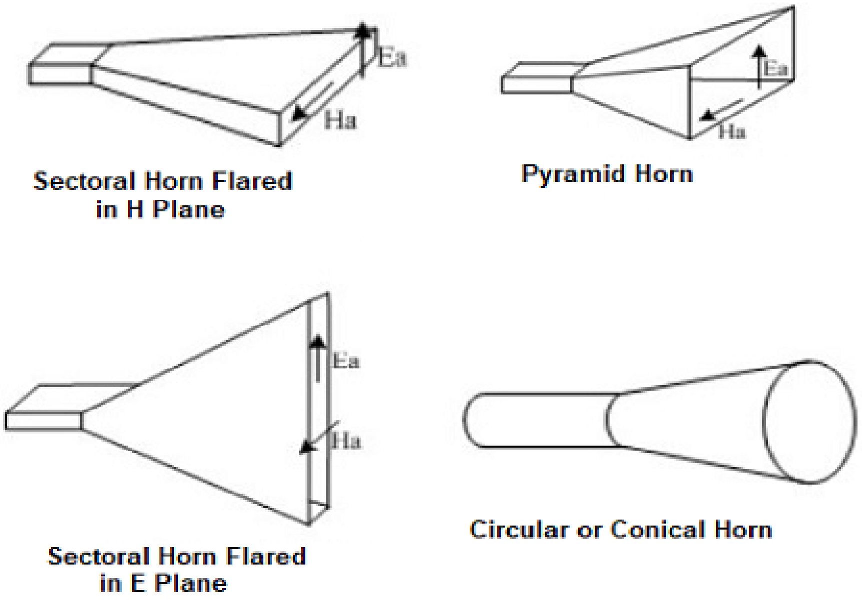


FIGURE 2.4. Horn Antenna

Parabolic Antennas : Parabolic antennas, also known as dish antennas, are a type of directional antenna that are designed to focus the radiation in a specific direction. They consist of a metal dish that is parabolic in shape and a feed element that is located at the focal point of the dish. Parabolic antennas are commonly used in satellite communication systems and in radio telescopes [13].

FIGURE 2.5. Parabolic Antenna

Helical Antennas : Helical antennas are a type of directional antenna that are designed to have a high gain and a circular polarization. They consist of a helical wire that is wound into a coil and a ground plane. Helical antennas are commonly used in satellite communication systems, as well as in wireless communication systems that require circular polarization [12].

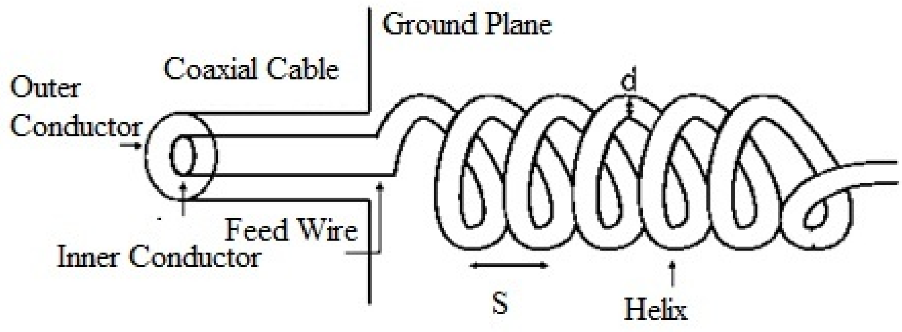


FIGURE 2.6. Helical Antenna

Log-Periodic Antennas : Log-periodic antennas are a type of broadband antenna that are designed to operate over a wide frequency range. They consist of a series of dipole elements that are arranged in a geometric pattern. Log-periodic antennas are commonly used in television broadcasting, as well as in communication systems that require a wide bandwidth [11].

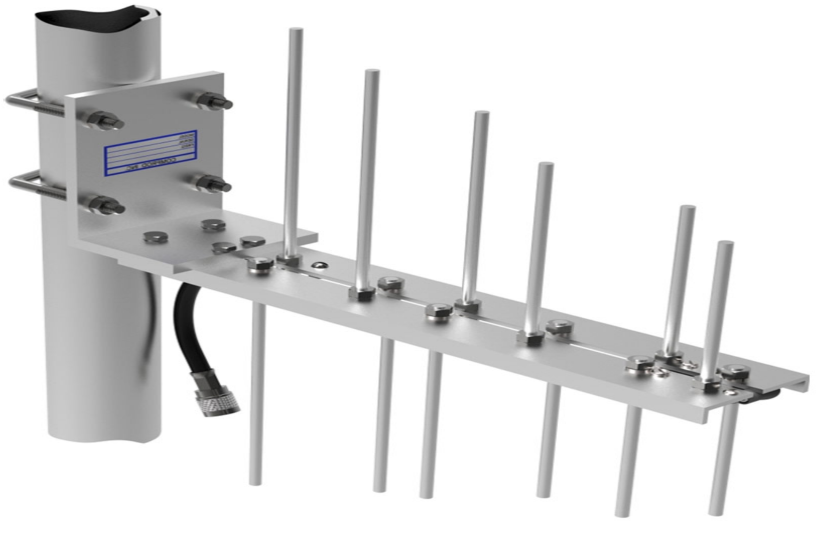


FIGURE 2.7. Log-Periodic Antenna

In conclusion, there are many types of antennas, each with its own characteristics and advantages. The choice of antenna depends on the application, frequency range, and design requirements. Understanding the different types of antennas is essential for designing and implementing effective communication systems.

2.2.2 Characteristics of the antennas

Antennas are fundamental components of communication systems that transmit and receive electromagnetic signals. The characteristics of antennas can affect the performance of a communication system, including its range, data rate, and reliability. Here are some of the key characteristics of antennas [14] :

Radiation pattern : The radiation pattern of an antenna describes how the electromagnetic energy is radiated in space. The radiation pattern can be directional or omnidirectional, and it can be measured in two or three dimensions. The radiation pattern determines the coverage area of the antenna and how well it can receive signals from different directions.

Gain : The gain of an antenna is a measure of how well it can focus the radiated energy in a particular direction. It is expressed as a ratio of the power radiated in a particular direction to the power that would be radiated by an isotropic antenna (an ideal antenna that radiates energy equally in all directions).

Bandwidth : The bandwidth of an antenna is the range of frequencies over which it can operate effectively. A wideband antenna can operate over a broad range of frequencies, while a narrowband antenna is designed to operate over a specific frequency range.

Impedance : The impedance of an antenna is a measure of how much resistance it offers to the flow of electromagnetic energy. Impedance matching is critical for achieving maximum power transfer between the antenna and the transmitter or receiver.

Polarization : The polarization of an antenna describes the orientation of the electromagnetic wave as it is radiated. The polarization can be vertical, horizontal, or circular, and it must match the polarization of the transmitted signal for efficient transmission.

Efficiency : The efficiency of an antenna is a measure of how much of the input power is radiated as electromagnetic energy. A high-efficiency antenna minimizes losses due to reflection, absorption, and radiation.

Size and weight : The size and weight of an antenna can be critical factors in many applications, especially in mobile communication systems where size and weight are often limited.

These are some of the key characteristics of antennas that can impact their performance and suitability for different applications. Antenna designers must carefully balance these characteristics to create an antenna that meets the specific requirements of a communication system.

2.2.3 Frequency bands for satellite communications

Satellite communications use a variety of frequency bands to transmit signals between the earth and the satellite. Here are some of the main frequency bands used for satellite communications [15] :

- **L-band** $[1-2GHz]$: L-band is used for both satellite navigation systems (such as GPS) and satellite communications. L-band signals have a long wavelength, which means that they can penetrate through obstacles such as clouds and foliage, making them ideal for mobile applications.
- **S-band** $[2-4GHz]$: S-band is commonly used for satellite communications and radar systems. It is also used for mobile satellite communications due to its ability to penetrate through obstacles.
- **C-band** $[4-8GHz]$: C-band is used for satellite communications, radar systems, and weather monitoring. It is less affected by rain and atmospheric interference than higher frequency bands, making it a reliable choice for critical applications.
- **X-band** $[8-12GHz]$: X-band is used for high-frequency satellite communications, radar systems, and military applications. It has a shorter wavelength than C-band, which makes it more focused and less prone to interference.
- **Ku-band** $[12-18GHz]$: Ku-band is used for satellite communications, including direct-to-home television (DTH), broadband internet, and voice services. It is less prone to interference than C-band and has a higher data rate than L-band.

— **Ka-band** $[26.5-40GHz]$: Ka-band is used for high-speed data communications, including satellite broadband and other high-bandwidth applications. It has a shorter wavelength than Ku-band, which means that smaller antennas can be used, but it is more susceptible to atmospheric interference.

The main difference between these frequency bands is their wavelength and frequency range. Lower frequency bands, such as L-band and S-band, have longer wavelengths and can penetrate through obstacles such as foliage, clouds, and rain. Higher frequency bands, such as Ka-band, have shorter wavelengths and are more focused, allowing for higher data rates but making them more susceptible to atmospheric interference. The choice of frequency band for a satellite communication system depends on the specific application requirements, such as the required data rate, the size of the antenna, and the potential for interference [11].

L-band (1-2 GHz)	Mobile satellite service (MSS) UHF TV, terrestrial microwave and studio television links, cellular phone
S-band (2-4 GHz)	MSS, Digital Audio Radio Service (DARS) NASA and deep space research
C-band (4-8 GHz)	Fixed Satellite Service (FSS), fixed service terrestrial microwave
X-band (8-12.5 GHz)	FSS military communication, DARS feeder links, fixed service terrestrial, Earth observation satellites
Ku-band (12.5-18 GHz)	FSS, Broadcast Satellite Service (BSS) fixed service terrestrial microwave
K-band (18-26.5 GHz)	BSS, FSS, fixed service terrestrial microwave, local multichannel distribution service (LMDS)
Ka-band (26.5-40 GHz)	FSS, fixed service terrestrial microwave, LMDS, Intersatellite links (ISL), satellite imaging

2.3 Waveguide technology

2.3.1 Classical waveguide

Microwaves propagate through microwave circuits, components and devices, which act as a part of Microwave transmission lines, broadly called as Waveguides.

2.3.1.1 Definition

A hollow metallic tube of the uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called as a waveguid.

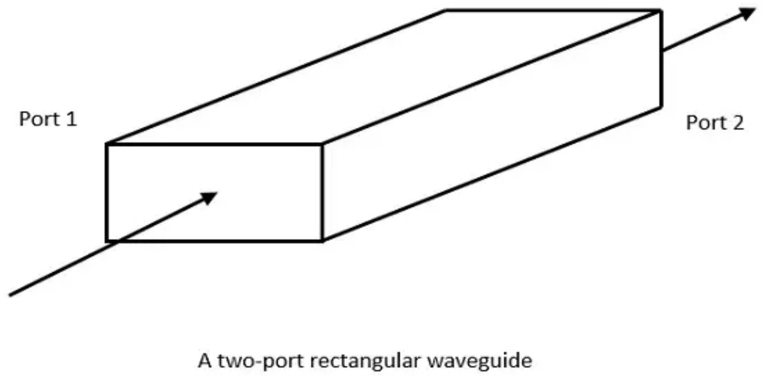


FIGURE 2.8. Rectangular waveguide

A waveguide is generally preferred in microwave communications. A waveguide is a special form of a transmission line, which is a hollow metal tube. Unlike the transmission line, the waveguide has no center conductor.

The Main Characteristics of A Waveguide Are :

1. The tube wall provides distributed inductance.
2. The empty space between the tube walls provide distributed capacitance.
3. These are bulky, heavy, and expensive.

2.3.1.2 Advantages of Waveguides

1. Waveguides are easy to manufacture.

2. They can handle very large power (in kilowatts).
3. Power loss is very negligible in waveguides.
4. They offer very low loss (low value of alpha-attenuation).
5. The microwave energy when travels through the waveguide, experiences lower losses than a coaxial cable.

2.3.1.3 Types of Waveguides

There are five types of waveguides. And They are :

Rectangular waveguides : This is the most common type of waveguide, and it has a rectangular cross-section. It is typically used for high-power applications in the microwave and millimeter-wave frequencies.

Circular waveguides : This waveguide has a circular cross-section and is often used for satellite communication systems and radar applications.

Elliptical waveguides : This is a variation of rectangular waveguides, with an elliptical cross-section. It is used for applications that require low-loss transmission at high frequencies.

Ridged waveguides : This waveguide has a ridge along its length, which helps to reduce the wavelength of the transmitted signal. It is often used in high-frequency applications.

Coaxial waveguides : This is a type of waveguide that uses two concentric conductors separated by a dielectric material. It is used in many applications, including cable television and high-frequency measurements.

Optical waveguides : These waveguides are used to guide light waves, and they are typically made of glass or plastic fibers. They are used in fiber-optic communication systems to transmit data over long distances.

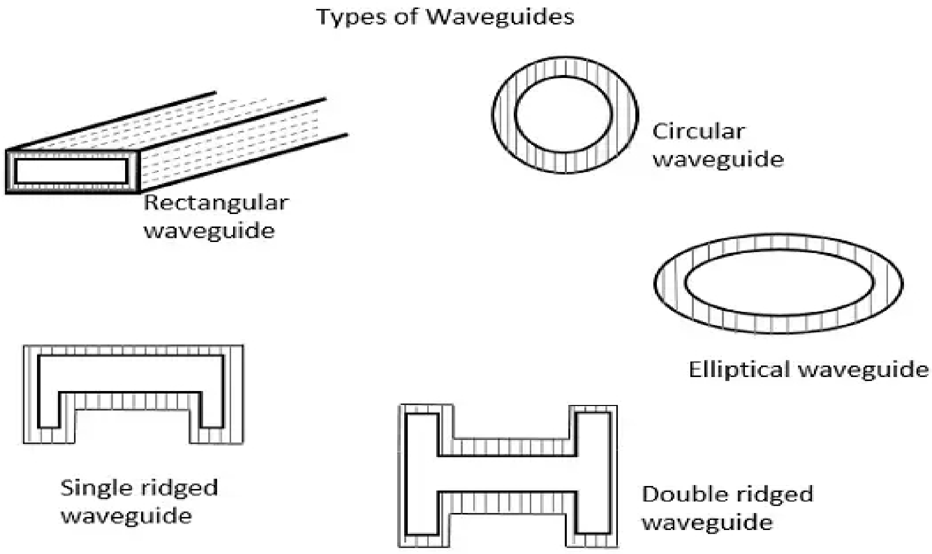


FIGURE 2.9. Optical classical waveguides

The above shown are the types of waveguides which are made hollow in the center and made up of copper walls. These have a thin lining of Au or Ag on the inner surface.

2.3.2 SIW technology

Substrate Integrated Waveguide (SIW) technology is a relatively new and innovative approach to microwave and millimeter-wave circuit design that combines the benefits of both conventional waveguide technology and planar microstrip technology. SIW technology involves the use of a dielectric substrate to support a metallic waveguide structure that is integrated into the substrate, resulting in a waveguide-like structure that can be fabricated using conventional printed circuit board (PCB) techniques [16].

SIW technology was first proposed by Jian-Ming Jin and Wei Hong in a paper published in 2002. The idea behind the technology was to create a waveguide structure that could be easily integrated into a planar substrate, allowing for the design and fabrication of compact and low-cost microwave and millimeter-wave circuits. Since then, the technology has rapidly developed and has found numerous applications in a wide range of industries, including aerospace, telecommunications, and automotive radar systems [16].

One of the key advantages of SIW technology is its ability to provide low-loss and high-power handling capabilities, which make it suitable for applications requiring high performance and reliability. The use of dielectric substrates also enables the design of compact and lightweight circuits that can be easily integrated into complex systems [16].

SIW technology has been used to design a wide range of components, including antennas, filters, couplers, power dividers, and amplifiers. The technology has also been used to develop new types of millimeter-wave systems, such as 5G wireless networks and automotive radar systems.

SIW technology represents a significant advancement in microwave and millimeter-wave circuit design, offering a range of benefits including high performance, low cost, and compact size. As the demand for higher frequencies and more integrated systems continues to grow, SIW technology is expected to play an increasingly important role in the development of future microwave and millimeter-wave systems [17].

2.3.2.1 Definition

Substrate integrated waveguide (SIW) technology is a relatively new and rapidly developing area of microwave and millimeter-wave technology that combines the benefits of conventional waveguide technology with the advantages of planar microstrip technology. SIW technology uses a dielectric substrate to support a metallic waveguide structure that is integrated into the substrate, creating a waveguide-like structure that can be fabricated using conventional printed circuit board (PCB) techniques [18].

In SIW technology, the waveguide structure is formed by etching a rectangular or circular cavity into the dielectric substrate and covering it with a metallic lid. The structure can be further optimized by adding metallic posts or irises to tune the resonance frequencies and improve the performance.

One of the key advantages of SIW technology is that it allows for the integration of multiple components into a single substrate, which reduces the complexity and size of the system. SIW structures can also be designed to have lower loss and higher power handling capabilities compared to microstrip technology [17].

SIW technology has a wide range of applications, including in antennas, filters, couplers, amplifiers, and other microwave and millimeter-wave components. It is particularly well-suited for applications that require high performance, compact size, and low cost, such as in wireless communication systems, satellite systems, radar systems, and automotive radar systems.

SIW technology offers a promising solution for designing and fabricating high-performance microwave and millimeter-wave components with a simple, low-cost, and compact form factor. As the demand for higher frequencies and more integrated systems continues to grow, SIW technology is expected to play an increasingly important role in the development of future microwave and millimeter-wave systems.

2.3.2.2 Fields of application of SIW technologie

Substrate Integrated Waveguide (SIW) technology has a wide range of applications in various fields. Here are some of the main fields of application of SIW technology [19] :

- **Telecommunications :** SIW technology is widely used in telecommunications systems such as cellular networks, satellite communication systems, and radar systems. SIW components such as filters, couplers, and antennas are commonly used in these systems due to their high performance and compact size.
- **Aerospace and Defense :** SIW technology is also used in aerospace and defense applications such as radar systems, electronic warfare, and satellite communication systems. The high performance and low loss of SIW components make them ideal for use in these systems.
- **Medical Devices :** SIW technology is used in medical devices such as MRI machines, PET scanners, and other medical imaging devices. SIW components can be used to create compact and high-performance components for these devices.
- **Automotive Applications :** SIW technology is used in automotive applications such as collision avoidance systems, radar systems, and communication systems. The high performance and low profile of SIW components make them ideal for integration into automotive designs.
- **Wireless Power Transfer :** SIW technology is used in wireless power transfer systems such as wireless charging pads and inductive power transfer systems. The high-Q resonant structures of SIW components make them suitable for efficient wireless power transfer.
- **Internet of Things (IoT) :** SIW technology is also used in IoT devices such as smart home devices, sensors, and wearables. The compact size and high performance of SIW components make them ideal for integration into IoT devices.

The versatility and high performance of SIW technology make it ideal for a wide range of applications in various industries. Its use in telecommunications, aerospace and defense, medical devices, automotive applications, wireless power transfer, and IoT devices is expected to continue growing in the coming years.

2.3.2.3 Characteristics of the SIW TECHNOLOGY

The substrate integrated waveguide (SIW) technology has several unique characteristics that make it an attractive choice for a variety of microwave and millimeter-wave applications :

- **Low loss :** The SIW structure offers low-loss transmission characteristics because the signal travels through a waveguide structure that confines the energy within the dielectric substrate. This reduces the electromagnetic radiation losses that are common in conventional microstrip and coplanar waveguide structures [20].
- **High-Q resonators :** The SIW technology allows for the implementation of high-quality factor (Q) resonators, such as cavity resonators and filters, due to the tight confinement of the electromagnetic fields in the waveguide structure [20].
- **Integration with planar circuits :** The SIW structure can be easily integrated with planar circuits using standard printed circuit board (PCB) technology. This allows for the integration of SIW-based components with other microwave and millimeter-wave components on a single PCB, which simplifies system integration [19].
- **Compact size :** The SIW technology allows for the implementation of compact and low-profile microwave components and systems. The SIW waveguide can be designed to have a very low profile, which can be useful for applications where space is limited [19].
- **Broadband operation :** The SIW technology can support broadband operation over a wide frequency range, making it suitable for applications that require wide bandwidths [19].
- **High power handling capability :** The SIW structure has a high power handling capability due to the waveguide-like structure, which can handle high power levels without significant losses or damage to the substrate [19].

- **Ease of fabrication :** The SIW technology can be easily fabricated using standard PCB fabrication techniques, which can significantly reduce the cost and complexity of manufacturing SIW-based components and systems [18].

These characteristics make the SIW technology an attractive choice for a variety of applications, including filters, antennas, power dividers, couplers, and other microwave and millimeter-wave components and systems.

2.3.3 Uses of the waveguide

Waveguides have a wide range of uses in various fields, including :

1. **Telecommunications :** Waveguides are used in telecommunications to transport signals over long distances with minimal loss of energy. They are commonly used in microwave and millimeter-wave applications, including in the construction of antennas, amplifiers, and filters, among others [21].
2. **Radar systems :** Waveguides are used in radar systems to guide and focus the transmitted signals. They are used in various radar applications, including weather radar, air traffic control radar, and military radar systems[21].
3. **Satellite communication :** Waveguides are used in satellite communication systems to transmit and receive signals. They are used in applications such as satellite television, internet, and telephone services [22].
4. **Medical equipment :** Waveguides are used in medical equipment such as magnetic resonance imaging (MRI) machines and other imaging systems [22].
5. **Scientific research :** Waveguides are used in scientific research, such as in particle accelerators, to guide and focus particle beams [22].
6. **Industrial applications :** Waveguides are used in industrial applications such as heating, drying, and welding, among others. They are used to generate high-power microwave and millimeter-wave energy for industrial processing applications [22].

Waveguides have numerous applications across various industries, and their ability to guide and focus electromagnetic waves makes them an essential component of many technological systems.

2.4 Patch antennas

Patch antennas are a type of antenna that are commonly used in wireless communication systems. They are also known as microstrip antennas, planar antennas, or printed antennas. They were first developed in the 1960s by researchers at the University of Illinois, and since then they have become one of the most widely used types of antennas due to their low profile, light weight, and ease of integration into electronic circuits.

A patch antenna consists of a thin metallic patch, usually made of copper, that is printed on a dielectric substrate. The patch is typically rectangular or circular in shape, although other shapes are also possible. The dielectric substrate can be made of various materials, such as FR4, Rogers, or Teflon, and its thickness is usually a fraction of the wavelength of the electromagnetic wave that the antenna is designed to radiate or receive.

Patch antennas are classified into two types : microstrip patch antennas and aperture-coupled patch antennas. In a microstrip patch antenna, the metallic patch is printed on one side of the dielectric substrate, while a ground plane is printed on the other side. The ground plane serves as a reflector that helps to direct the radiation from the patch in the desired direction. In an aperture-coupled patch antenna, the metallic patch is placed on one side of a substrate, while a feeding structure, usually a slot or aperture, is placed on the other side. The electromagnetic wave is coupled from the feeding structure to the patch through the aperture.

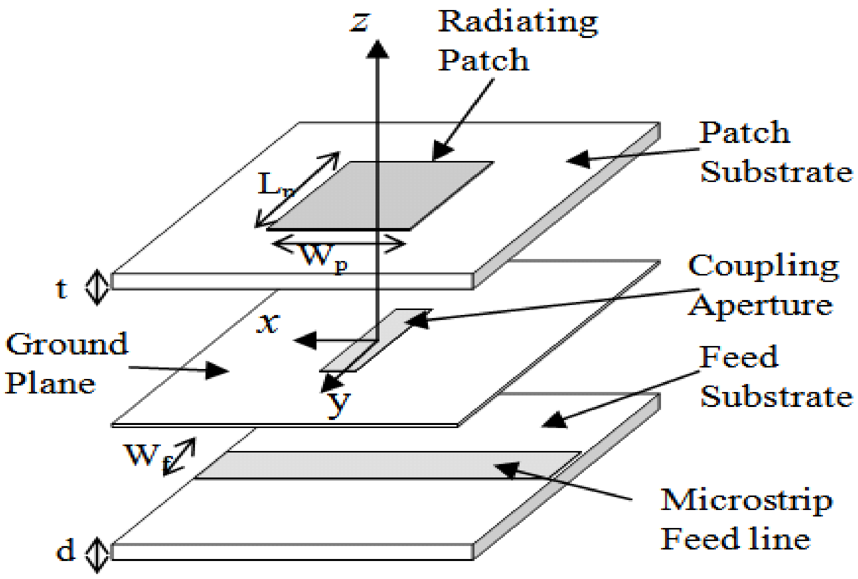


FIGURE 2.10. Patch antenna design

Patch antennas have many advantages over other types of antennas. They are small in size, low profile, and lightweight, making them easy to integrate into electronic devices. They can also be fabricated using low-cost manufacturing processes, such as printed circuit board (PCB) technology. Furthermore, their radiation patterns can be easily controlled by adjusting the shape and size of the patch and the substrate [23].

Patch antennas are commonly used in various applications, such as wireless communication systems, satellite communication systems, radar systems, and sensing systems. They are also used in mobile devices, such as smartphones and tablets, due to their low profile and small size. In addition, patch antennas are used in radio frequency identification (RFID) systems, where they serve as the antennas for the RFID tags [23].

In summary, patch antennas are a versatile and widely used type of antenna that offer many advantages over other types of antennas. They are small in size, low profile, lightweight, and easy to integrate into electronic circuits. They are commonly used in various applications, such as wireless communication systems, satellite communication systems, radar systems, and sensing systems, as well as in mobile devices and RFID systems [23].

2.4.1 Fields of application of patch antennas

Patch antennas have a wide range of applications due to their compact size, low profile, and ease of integration into electronic devices. Some of the most common applications of patch antennas include :

1. **Wireless communication :** Patch antennas are commonly used in wireless communication systems such as Wi-Fi, Bluetooth, and GPS. They can be integrated into mobile devices, laptops, and other wireless devices to provide reliable wireless connectivity [23].
2. **RFID systems :** Radio-frequency identification (RFID) systems use patch antennas to communicate with RFID tags. Patch antennas can be used to read and write data to RFID tags, making them ideal for applications such as inventory tracking, access control, and asset management [21].
3. **Aerospace and defense :** Patch antennas are widely used in aerospace and defense applications such as satellite communication, radar, and navigation systems. Their low profile and lightweight make them ideal for use in airborne or space borne sys-

tems.

4. **Medical devices :** Patch antennas are used in medical devices such as pacemakers, implants, and sensors. They can be used to wirelessly transmit data and power to medical devices, eliminating the need for bulky wires and cables [20].
5. **Automotive applications :** Patch antennas are commonly used in automotive applications such as GPS navigation systems, satellite radio, and remote keyless entry systems. Their low profile and small size make them ideal for integration into automotive designs.
6. **Consumer electronics :** Patch antennas are used in a wide range of consumer electronics such as smartphones, tablets, and smartwatches. They can be used to provide wireless connectivity for internet access, streaming media, and other applications.

The versatility and compact size of patch antennas make them ideal for a wide range of applications in various industries. Their low profile and ease of integration into electronic devices make them a popular choice for wireless communication, aerospace and defense, medical devices, automotive applications, and consumer electronics.

2.4.2 Patch antenna calculations

In antenna patch calculations, various calculations are essential for designing and analyzing the performance of patch antennas. Here is an overview of the important calculations involved, along with the equations associated with each calculation :

2.4.2.1 Patch Dimensions

The length (L) and the width (W) of the patch antenna can be determined based on the desired resonant frequency (f_0) and the wavelength (λ) of operation [12].

$$L = \frac{\lambda}{2} \tag{2.1}$$

The area of the patch (A) affects the antenna's radiation properties [17]. It given by

$$A = L \times W \tag{2.2}$$

2.4.2.2 Substrate Parameters :

Relative permittivity (ε_r) determination : The substrate material's permittivity affects the antenna's electrical characteristics [10].

$$\varepsilon_r = \varepsilon_{r_0} - j\varepsilon_{r_i} \tag{2.3}$$

Substrate thickness (h) selection : The substrate thickness impacts the antenna's impedance matching and radiation pattern [13].

$$h = \frac{\lambda}{2} \tag{2.4}$$

2.4.2.3 Resonant Frequency

Half-wavelength resonance calculation : The resonant frequency of the patch antenna can be determined based on the length or width of the patch [2].

$$f_0 = \frac{c}{2L} \tag{2.5}$$

Quarter-wavelength resonance calculation : The resonant frequency can also be calculated based on the effective electrical length of the patch [3].

$$f_0 = \frac{c}{4W\sqrt{\varepsilon_r}} \tag{2.6}$$

2.4.2.4 Impedance Matching

Input impedance (Z_{in}) calculation : The input impedance of the patch antenna needs to be matched to the characteristic impedance (Z_0) of the feeding network for efficient power transfer [5].

$$Z_{in} = R + jX \tag{2.7}$$

Reflection coefficient ($\varGamma$) calculation : The reflection coefficient quantifies the impedance mismatch and is used to evaluate the matching performance [10].

$$\varGamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{2.8}$$

2.4.2.5 Radiation Pattern :

Far-field pattern calculation : The radiation pattern of the patch antenna describes the spatial distribution of radiated power.

$$E(\theta,\varphi) = \sqrt{G(\theta,\varphi) \times E_0} \tag{2.9}$$

Directivity (D) calculation : Directivity measures the radiation intensity in the direction of maximum radiation [3].

$$D = 4\pi G(\theta,\varphi) \tag{2.10}$$

Beamwidth calculation : Beamwidth represents the angular width of the main lobe of the radiation pattern [6].

$$Beamwidth = 2\theta_{halfpower} \tag{2.11}$$

2.4.2.6 Bandwidth

Quality factor (Q) calculation : The quality factor represents the sharpness of the resonance and influences the bandwidth [23].

$$Q = \frac{f_0}{\Delta_f} \tag{2.12}$$

Bandwidth calculation : The bandwidth is determined based on the quality factor and the resonant frequency [13].

$$\Delta_f = \frac{f_0}{Q} \tag{2.13}$$

2.4.2.7 Polarization

Linear polarization calculation : The patch antenna can exhibit linear polarization based on its geometry and feed structure [21].

$$E_{field} = E_0 \times \cos(\theta) \times \cos(2\pi f_0 t) \tag{2.14}$$

2.4.2.8 Efficiency

Antenna efficiency calculation : Efficiency measures how effectively the antenna converts input power into radiated power [10].

$$\eta = \frac{P_{rad}}{P_{in}} \tag{2.15}$$

These equations, combined with simulations using software tools like HFSS, facilitate the design, analysis, and optimization of patch antennas. They enable engineers to achieve desired performance characteristics and meet the requirements of wireless communication systems.

2.5 Conclusion

In conclusion, antennas play a vital role in communication systems by facilitating the transmission and reception of electromagnetic waves. The choice of antenna depends on specific requirements such as application, frequency range, and design. Understanding the characteristics of antennas, including radiation pattern, gain, bandwidth, impedance, polarization, efficiency, size, and weight, is essential for designing effective communication systems. Additionally, antenna arrays, which consist of multiple antennas arranged in specific patterns, offer further flexibility in achieving desired radiation patterns. Moreover, satellite communications utilize different frequency bands, such as L-band, S-band, C-band, X-band, Ku-band, and Ka-band, each with its own advantages and limitations., antennas and their associated technologies are key components for enabling effective wireless communication in various domains.

Chapter 3

Antenna simulation and results

3.1 Introduction

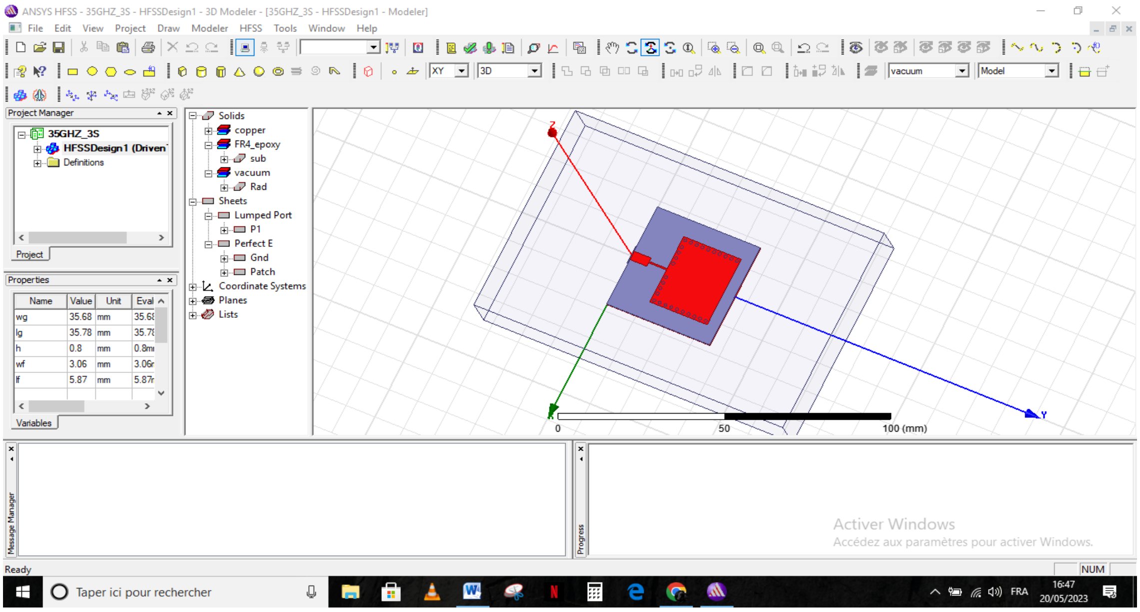
In this chapter, we will first introduce the HFSS simulation software. We will show its various windows, the process, and the operation of this software. We will propose a structure of a patch antenna operating in the frequency [28 GHz]. The simulation results are presented in the form of S11, Patern recognition and VSWR. Then, we will explore the influence of certain geometric parameters of the patch antenna on its operation.

3.2 HFSS electromagnetic field simulation software

HFSS (High Frequency Structure Simulator) is software that calculates the electromagnetic behavior of a structure. To analyze this behavior in detail, the software provides us with post-processing interpretation tools. It performs electromagnetic modeling by solving Maxwell's equations using the finite element method. The principle of the method used is to divide the study space into a large number of small regions, and then calculate the local electromagnetic field in each element. We simulated SIW antennas using Ansoft's HFSS software. The choice of this software for our application is justified. Indeed, it is dedicated to high-frequency simulation of microwave circuits. It is a powerful simulation software that allows for the representation of field distributions and the calculation of parameters for passive microwave structures. An HFSS project is a folder that contains one or more design models. Each model contains a geometric structure, its boundary conditions, material choices, as well as electromagnetic field solutions and post-processing interpretations [24].

3.2.1 Main Interface of HFSS

The main interface of HFSS (High Frequency Structure Simulator) provides a comprehensive set of tools and features for electromagnetic simulation. The interface is designed to facilitate the setup, analysis, and visualization of the simulated structures [24].



Name	Value	Unit	Eval
wg	35.68	mm	35.68
lg	35.78	mm	35.78
h	0.8	mm	0.8mm
wf	3.06	mm	3.06mm
lf	5.87	mm	5.87mm

FIGURE 3.1. Main Interface of HFSS

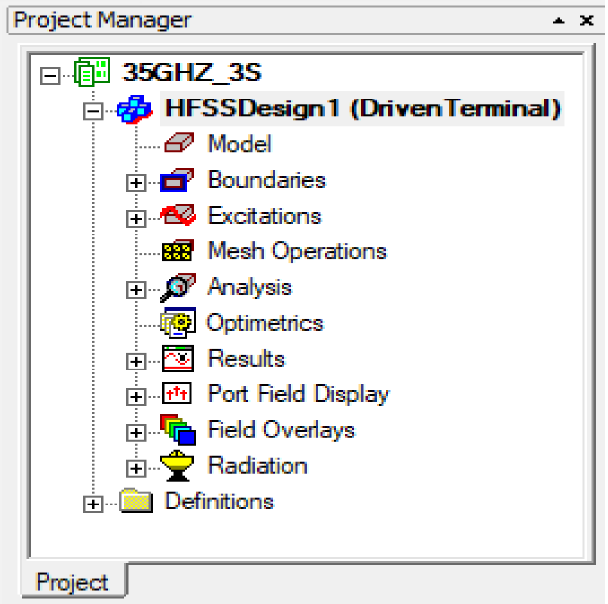


FIGURE 3.2. Management Tree of a Structure in HFSS

3.2.2 Process and Operation of HFSS

The following flowchart presents the process and operation of the HFSS software :

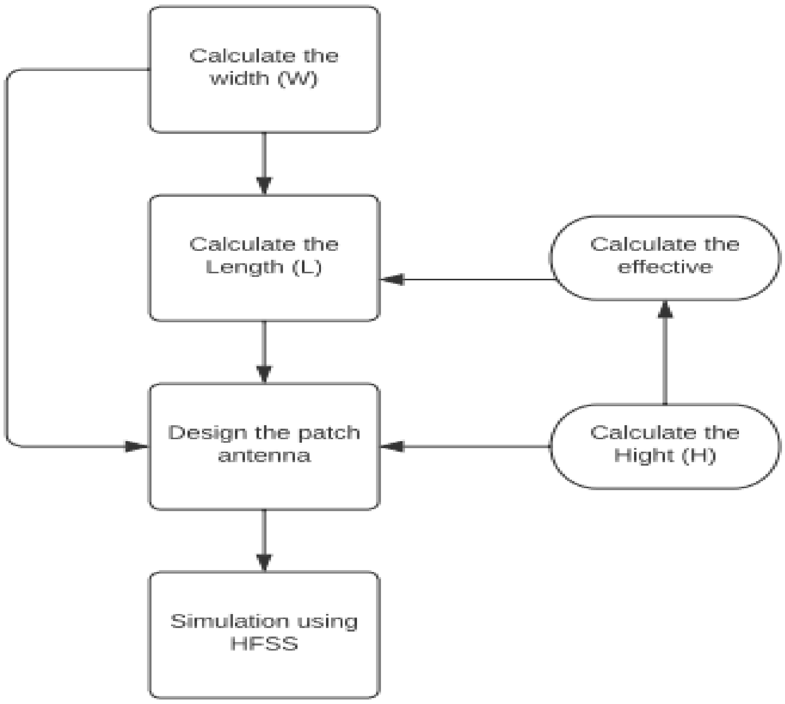


FIGURE 3.3. Design flow of patch antenna

3.2.2.1 Creation of projects by HFSS

In the File menu,

- Click on **New**.
- Specify the project name when saving it using the path : **File > Save** or **File > Save As**.
- To open a previously saved project, use the command : **File > Open**.
- To design a structure in HFSS, follow this general process.

It should be noted that after inserting a design, there is no need to execute the steps sequentially, but they must be completed before a solution can be generated.

3.2.2.2 Insertion of an HFSS design into a project

The new design is listed in the project tree. It is called **"HFSS Design"** by default, where [number] is the order in which the design was added to the project.

— The 3D modeling window appears to the right of the project management window. Now we can create a model of the geometry.

— We can choose the "Rescale to new" unit option to adjust the dimensions to the new units.

— Clear the "Rescale to new" unit option (default) to convert the dimensions to new units without changing the structure.

— Click on OK to apply the new units to the model.

3.2.2.3 Draw a model

To create a 3D structure, simply draw it using the tools provided by the software. Here, we will only describe the most challenging parts to implement. 3D objects can be created using the drafting commands of HFSS (HFSS Draw-commands). Objects are drawn in the 3D modeler window.

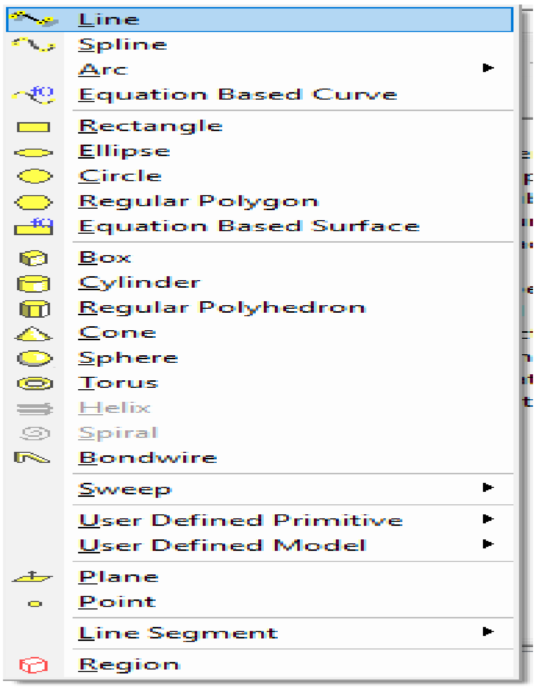
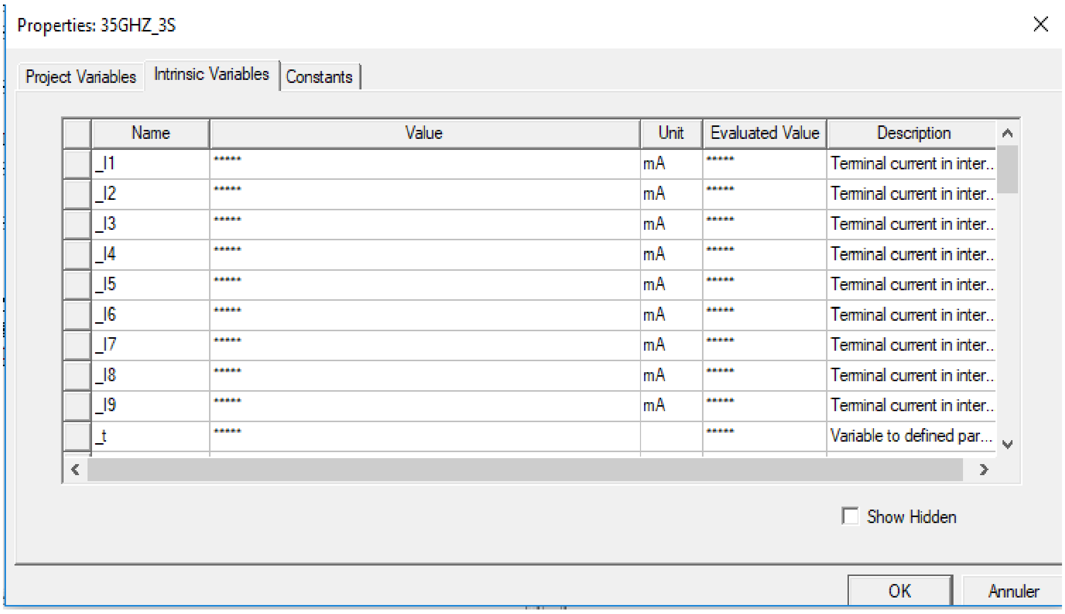


FIGURE 3.4. Structure Drawing tools

3.2.2.4 Using project variables

HFSS allows us to define variables and associate them with certain parameters of the structure, such as dimensions and material properties. Using variables to associate dimensions simplifies any potential changes to these parameters. For example, in our case, to change the excitations and dimensions of the plot, we only need to modify the value of the corresponding variable. To define a variable, select **Project > Project Variables** and enter its name, value, and unit. Once a variable is defined, we can use its name instead of its value. HFSS also allows us to use mathematical functions with defined variables.



Name	Value	Unit	Evaluated Value	Description
_I1	*****	mA	*****	Terminal current in inter..
_I2	*****	mA	*****	Terminal current in inter..
_I3	*****	mA	*****	Terminal current in inter..
_I4	*****	mA	*****	Terminal current in inter..
_I5	*****	mA	*****	Terminal current in inter..
_I6	*****	mA	*****	Terminal current in inter..
_I7	*****	mA	*****	Terminal current in inter..
_I8	*****	mA	*****	Terminal current in inter..
_I9	*****	mA	*****	Terminal current in inter..
_t	*****		*****	Variable to defined par...

FIGURE 3.5. Variables define

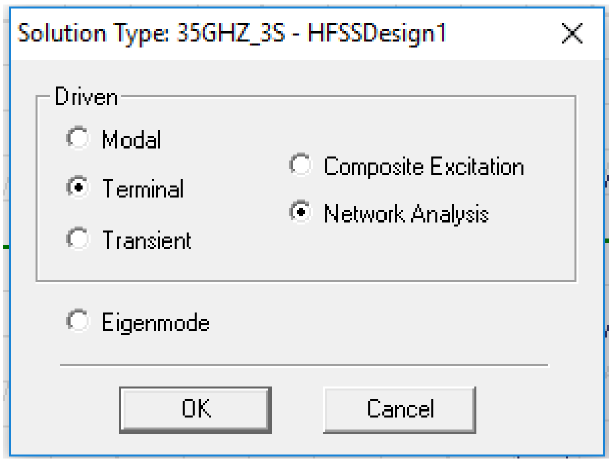
3.2.2.5 Subtraction of objects

It often happens that we want to remove certain parts of an object.

- Draw the main object as well as the objects that we want to subtract from it.
- Select the main object.
- While holding down the CTRL button, select the objects we want to subtract.
- Click on Subtract.
- Objects listed under "Tool Parts" are to be subtracted from the objects listed under "Blank Parts".
- If we want HFSS to keep a copy of the subtracted objects, we check the option "Clone tool objects before subtract".
- Press OK.

3.2.2.6 Types of Solutions in HFSS

The first step in performing a simulation is to determine the type of solution we want to achieve. The available access types and the obtained results depend on the selected solution type. So, in the HFSS menu, click on Solution Type, and the solution type dialog window will appear.



Solution Type: 35GHZ_3S - HFSSDesign1

Driven
○ Modal
● Terminal
○ Transient
○ Composite Excitation
● Network Analysis

○ Eigenmode

FIGURE 3.6. Solution type dialog

The second step is to choose the model type within the solution types. HFSS provides us with three different solution types, each optimized for a specific problem :

Driven Modal : This type is used when we want HFSS to calculate modal-based S-parameters of a passive structure at high frequencies, such as coplanar lines, waveguides, and resonant cavities. In this case, the S-parameters will be calculated based on the incident and reflected waves.

Driven Terminal : This type is used when we want HFSS to calculate modal-based S-parameters of multi-conductor transmission lines. In this case, the S-parameters will be calculated based on the voltage and current at the terminals.

Eigenmode : This type is used to calculate the resonances of a structure. The software will find the resonant frequency of the structure and the fields at those frequencies.

3.2.2.7 Exciting a Structure

After drawing a structure, in order for the software to perform the simulation, it is necessary to excite the structure. There are several types of excitations. Most commonly, Wave Ports and Lumped Ports are used.

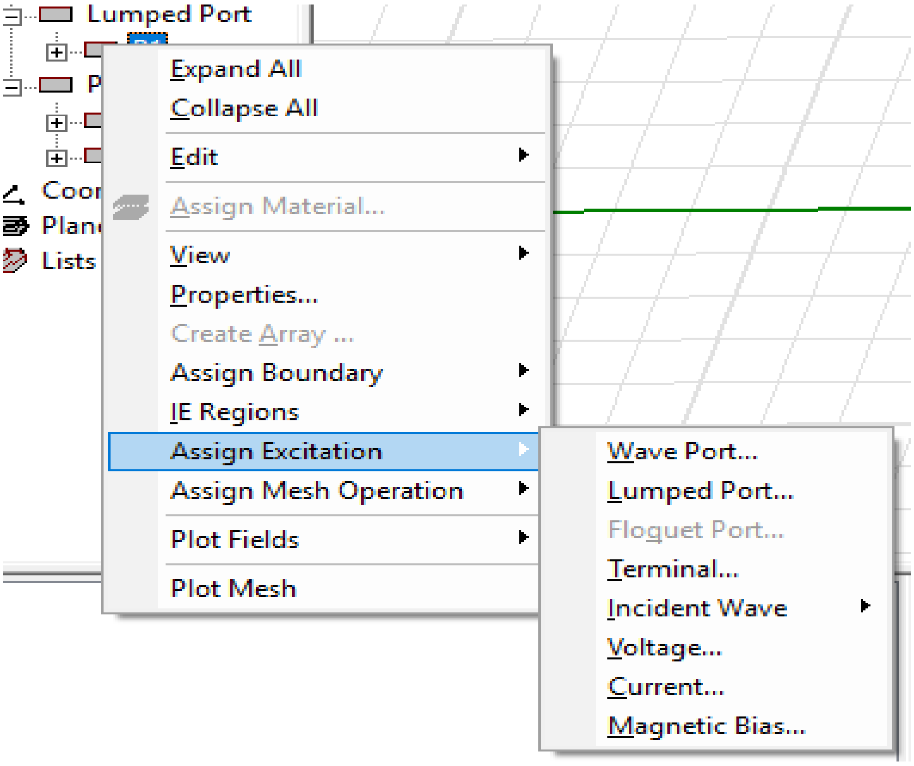


FIGURE 3.7. Excitation assignment

3.3 Design of SIW Antenna

The proposed SIW antenna operates in [28GHz]. Figure 3.8 shows the basic structure of this antenna in HFSS. It consists of one port : the input port (P1). The used substrate is an Rogers RT/duroid 58000 (tm) with a dielectric permittivity of ($\varepsilon_r = 2.2$) with a thickness of $h = 0.787mm$.

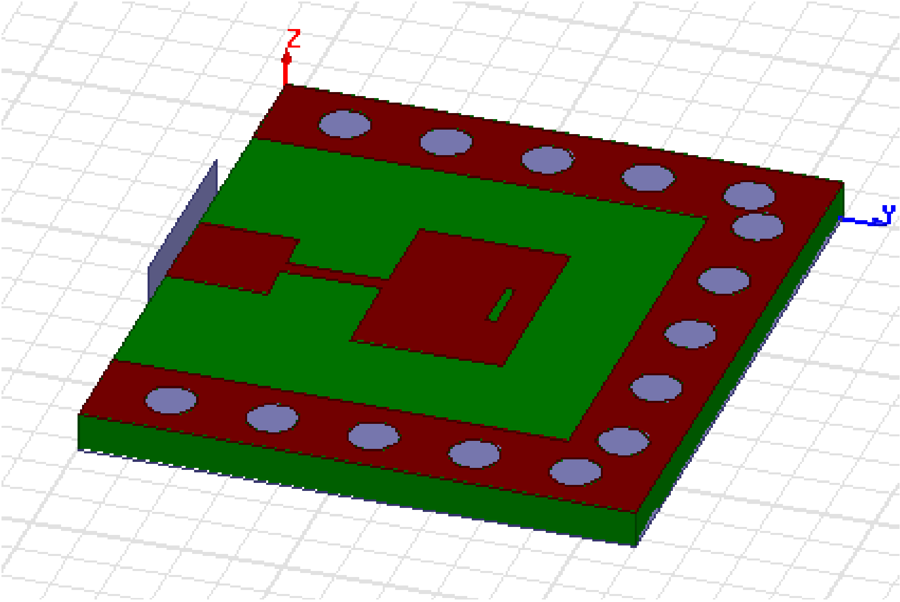


FIGURE 3.8. Proposed structure for SIW antenna

We will study the behavior of this antenna based on the distance between the central vias and the offset of each row relative to the center. Table 6 shows the four structures that have been studied.

3.3.1 Calculation for the Antenna Width (Ws)

The Width of micro strip patch antenna is given by eqn :

$$Ws = \frac{C}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{3.1}$$

Where,

- C is velocity of light,
- f_0 is a resonant frequency and
- ε_r is a relative dielectric constant.

In this equation we are substituting

- $C = 3 * 10^{11} mm/s$,
- $\varepsilon_r = 2.2$
- and $f_0 = 28GHz$,

Finally by solving this equation we get the width value as $Ws = 4.2mm$.

3.3.2 Calculating the Height of the Antenna

The height (H_s) of the antenna is given by 3.2 and is written as,

$$H_s = \frac{C}{2\pi f_0 \sqrt{\varepsilon_r}} \tag{3.2}$$

By substituting all the values and solving the equation we get the height of the antenna as $H_s = 1.14mm$ for 28GHz or the height of the used substrate is $H_s = 0.787mm$ and it is used for the simulation [25].

3.3.3 Calculating the Antenna Length (Ls)

It includes four steps :

Effective Dielectric Constant Before calculating the length of the antenna we should calculate the several other computations, the first step is to find the effective dielectric constant of the substrate.

The effective dielectric constant value should be closer to the dielectric constant of the substrate. The effective dielectric constant value is given by :

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{H_s}{W_s}\right]^{\frac{-1}{2}} \tag{3.3}$$

By substituting all the values and solving the equation we get the effective dielectric constant value as $1.93mm$ for 28GHz [25].

3.3.3.1 Extensive Length

The tangential fields of an antenna are in phase and by combining they will produce the maximum radiation pattern along the two sides of the antenna. The micro strip antenna looks larger in size when compared to its actual size due to its fringing fields so the length of the antenna is extended by its two sides along a path distance of Δ_L and it is given by

$$\Delta_L = 0.412\, H_s \frac{(\varepsilon_{re} + 0.3)\left(\frac{W_s}{H_s} + 0.264\right)}{(\varepsilon_{re} - 0.258)\left(\frac{W_s}{H_s} + 0.8\right)} \tag{3.4}$$

By substituting all the values and solving the equation we get the extensive length of the antenna as $0.19mm$ for $28\mathrm{GH}z$.

3.3.3.2 Effective Length of the Antenna

The effective length of the of antenna is given in 3.5 and which helps to find the original length of the rectangular micro strip patch antenna and it is written as

$$L_{eff} = \frac{C}{2f_0\sqrt{\varepsilon_{re}}} \tag{3.5}$$

This is used to calculate the narrow bandwidth of the antenna structure and various parameters of the antenna. By substituting all the values and solving the equation we get the effective length of the antenna as $3.85mm$ for $28\mathrm{GH}z$.

3.3.3.3 Actual Length of the Antenna

The actual length of the antenna is calculated by substituting the effective length and the extensive length of the antenna is given by

$$L_s = L_{eff} - 2\Delta_L \tag{3.6}$$

By substituting all the values and solving the equation we get the length of the antenna as $3.4mm$ for $28\mathrm{GH}z$.

3.4 Simulation results using HFSS

Nowadays it has become common to check the system performance through simulation before making it as real time application. A simulator **"Ansoft HFSS"** is used to check the gain, directicity, return loss, polarization, and radiation pattern. This simulator helps to reduce the cost of fabrication.

3.4.1 Antenna frequency response

The figure 3.9 shows the geometry of the proposed antenna. This antenna is intended to operate in the 28 $\mathrm{GH}z$ frequency.

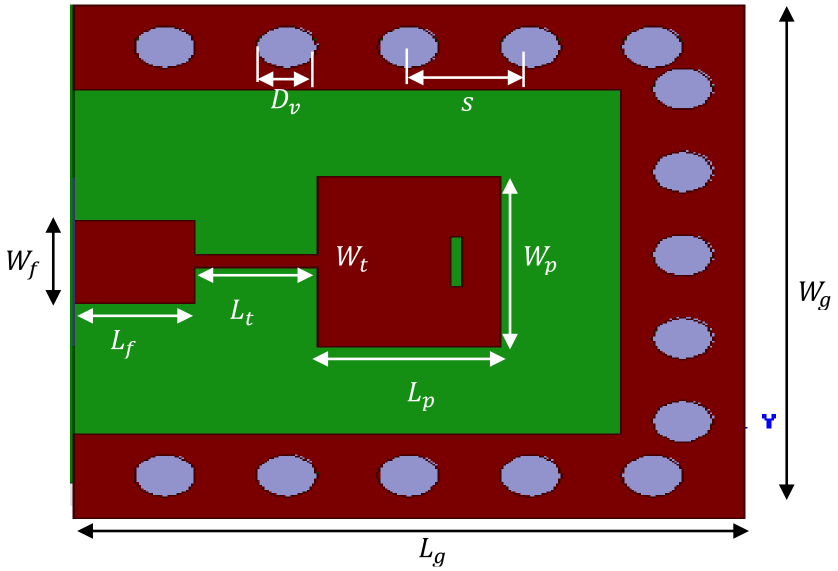


FIGURE 3.9. Proposed Antenna structure

Table 3.1 shows the dimensional parameters of the antenna. The substrate used is Rogers RT/duroid 58000(tm) with a permittivity of ($\varepsilon_r = 2.2$ and height of $h = 0.787$ mm).

TABLEAU 3.1. Dimensions of the proposed antenna

Parameters	**Description**	**Dimension**
W_G	Width of ground plane	12.3 mm
L_G	Length of the ground	11 mm
W_p	Width of the basic element (patch)	4.1 mm
L_p	Length of the basic element (patch)	3 mm
L_f	Feed line length	5.15 mm
W_f	Feed line width	2 mm
W_t	Transition width	0.32 mm
L_t	Transition Length	4.49 mm

Using the HFSS software, we measure the reflection coefficient, the pattern radiation, the gain and the antenna directivity. The antenna is analyzed in a frequency band of [25−−31 GHz], when the working frequency is fixed at 28 GHz.

Figure 3.10 illustrates the reflection coefficient S_{11} obtained. This antenna has a peak frequency of $f = 27.988$ GHz with an adaptation of $S_{11} = 18.62$ dB. This antenna shows a

2.126 GHz frequency band from 27.009 GHz to 29.135 GHz. Which is an important solution for 5G. applications.

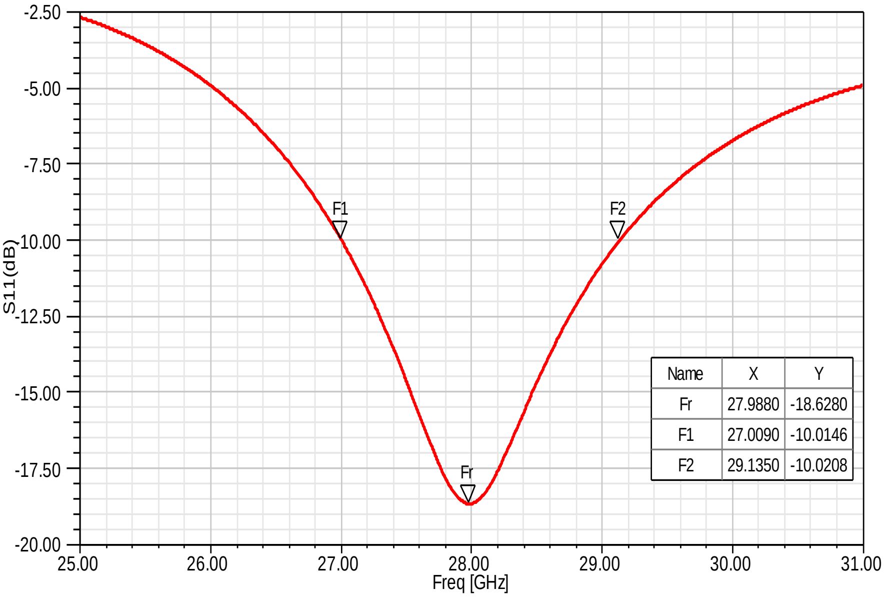


FIGURE 3.10. Frequency response at 28GHz

3.4.2 Antenna pattern radiation

There are a multitude of ways to represent the radiation diagram, for example power diagram or field diagram. The figure 3.11 shows the radiation pattern in (A) 2D and (B) 3D. The radiation pattern of this antenna is simulated in the E plane (ϕ = 0) and H plane (ϕ = 90). Note that the antenna radiates in a single direction with a main lobe.

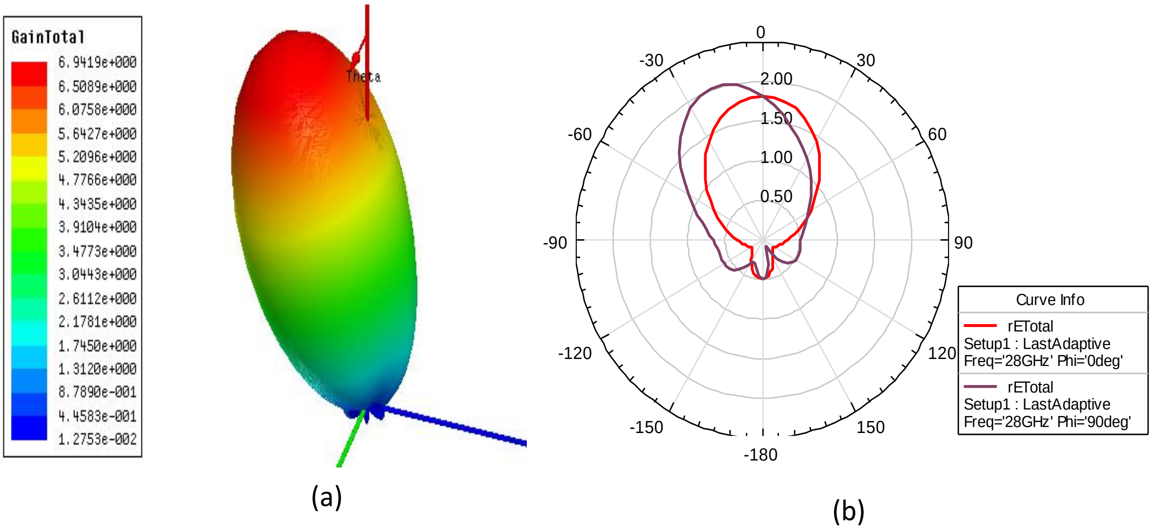


FIGURE 3.11. Radiation pattern

The design and analysis of the patch antenna was designed at a frequency range of 28GHz. The patch antenna is more advantageous than other types because their design structure is simple and have positive radiated edges on the both sides of the antenna.

3.4.3 Antenna gain

From the 3d radiation pattern, we can measure the gain of this antenna. It shows a gain of 6.9 in the main lobe, which is acceptable for a patch antenna.

3.4.4 Voltage Standing Wave Ratio

The VSWR is another very important parameter for antenna design. The figure shows the variation of VSWR as a function of frequency. It shows a value of 1.2653 for the working frequency 28GHz, this value is less than 2 which allows us to say that this antenna is well suited.

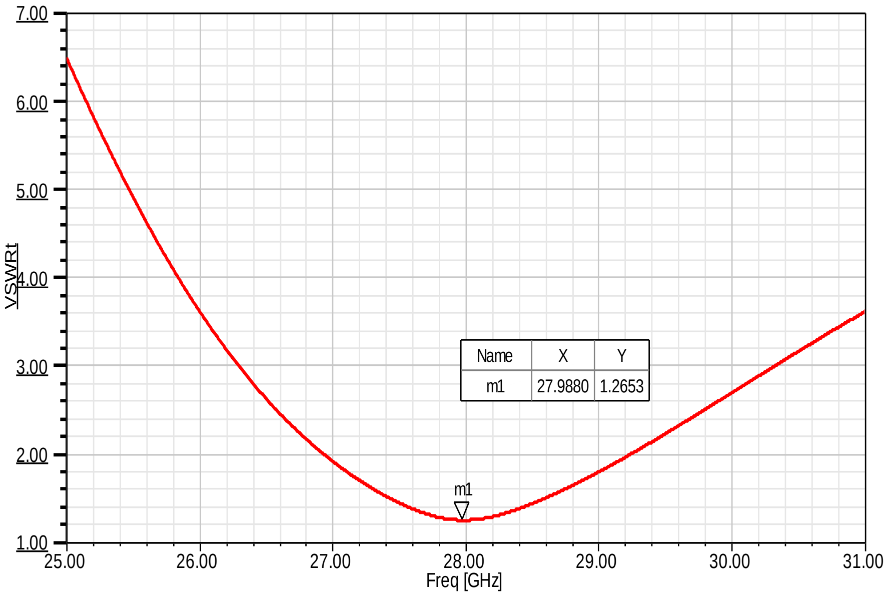


FIGURE 3.12. Voltage Standing Wave Ratio

3.5 Conclusion

During this chapter, we presented the simulation procedure and the results of the proposed antennas using the HFSS software. These results combine the reflection coefficient, the radiation pattern, the gain and the VSWR of antenna. This study improve the important performance of the proposed antenna to work with 5G systems.

General Conclusion

In conclusion, the next generation of cellular network technology, 5G, brings significant improvements in data speeds, latency, and connectivity. It comprises the Radio Access Network, Core Network, and User Equipment, all working together to provide enhanced capabilities. Antennas play a crucial role in 5G networks, utilizing millimeter waves and massive MIMO technology for beamforming, which improves signal strength and reduces interference.

One important frequency band for 5G operation is the 28 GHz band. This frequency range offers several benefits for wireless communication. Firstly, it provides a good balance between coverage and capacity. The 28 GHz frequency can propagate over moderate distances while still allowing for high data rates. This makes it suitable for deploying 5G networks in urban areas where a dense population requires both wide coverage and high capacity.

Furthermore, the 28 GHz band enables efficient spectrum utilization. It allows for the allocation of larger bandwidths, which translates to higher data transfer rates. With 5G, the 28 GHz frequency can support wider channels, providing faster download and upload speeds for various applications, including video streaming, online gaming, and large file transfers.

In terms of antenna design and simulation, HFSS (High Frequency Structure Simulator) proves to be a valuable tool. HFSS allows engineers to analyze and optimize antennas operating at the 28 GHz frequency band. By simulating the behavior of the antenna structures, it becomes possible to fine-tune their parameters and improve their performance characteristics such as gain, radiation pattern, and efficiency.

The utilization of the 28 GHz frequency in 5G networks, coupled with effective antenna design using tools like HFSS, contributes to the realization of the full potential of 5G technology. The 28 GHz band offers a favorable balance between coverage and capacity, enabling efficient and high-speed wireless communication in urban areas. As 5G continues to evolve, the 28 GHz frequency will play a crucial role in delivering seamless connectivity and unlocking the benefits of emerging applications and services, transforming various industries and enhancing user experiences.

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