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Design of Microstrip Array Antenna for 5G Mobile Communication Systems

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ABSTRACT:

The fifth generation (5G) of mobile technologies has become a promising and important cutting-edge technology in wireless communications systems for both academic and industrial concerns. However, the performance of these systems is significantly influenced by a wide range of factors, such as weather, multi-path effects and design of an efficient antenna. As a result, the improvement and innovation of antenna configurations will inevitably lead to upgrading the overall performance of wireless communication systems and can also pave the way for new applications. Recent research shows that new materials and metamaterials with unique features will enable antennas to be much smaller and more immune to interference.

The aim of this dissertation is to investigate and design a multi-service millimeter antenna for a 5G application. The project combines theoretical, methodological, and conceptual work, leading to the design and optimization of a microstrip patch array, which resonates at the frequency of 5G (28GHz). A photonic crystal is proposed to enhance the directivity and the realized gain of the antenna design. The microstrip patch array with a photonic crystal has to achieve a high gain and a high bandwidth in both bands of operation.

We designed two antennas for 5G applications using the CST software, which are low-cost to produce and very easy to manufacture for 5G applications. The obtained results on the most important characteristics of the antenna, such as the return loss, the radiation pattern, the gain, and the standing wave ratio (VSWR) of the antenna have been presented and discussed.

Keywords: Fifth generation (5G), millimeter band, microstrip patch antenna array, photonic crystal, CST Microwave Studio, Radiation characteristic.

RÉSUMÉ :

La cinquième génération (5G) de technologies mobiles est devenue une technologie de pointe prometteuse et importante dans les systèmes de communications sans fil pour les entreprises universitaires et industrielles. Cependant, le rendement de ces systèmes est grandement influencé par un large éventail de facteurs, comme les conditions météorologiques, les effets de trajets multiples et la conception d'une antenne efficace. Par conséquent, l'amélioration et l'innovation des configurations d'antennes entraîneront inévitablement une amélioration des performances globales des systèmes de communication sans fil et peuvent également ouvrir la voie à de nouvelles applications. Des recherches récentes montrent que les nouveaux matériaux et méta matériaux aux caractéristiques uniques permettront aux antennes d'être beaucoup plus petites et immunisées contre les interférences.

Le but de cette mémoire est d'étudier et de concevoir une antenne millimétrique multiservice pour une application 5G. Le projet combine des travaux théoriques, méthodologiques et conceptuels, menant à la conception et à l'optimisation d'un réseau de correctifs de microstrip, qui résonne à la fréquence de 5G (28GHz). Un cristal photonique est proposé pour améliorer la directivité et le gain réalisé de la conception de l'antenne. Le patch de microstrip avec un cristal photonique doit atteindre un gain élevé et une bande passante élevée dans les deux bandes de fonctionnement.

Nous avons conçu deux antennes pour les applications 5G à l'aide du logiciel CST, qui sont peu coûteuses à produire et très faciles à fabriquer pour les applications 5G. Les résultats obtenus sur les caractéristiques les plus importantes de l'antenne, telles que la perte de retour, le diagramme de rayonnement, le gain et le rapport d'onde stationnaire (VSWR) de l'antenne ont été présentés et discutés.

Mots-clés: Cinquième génération (5G), bande millimétrique, réseau de patchs microruban, cristaux photonique, CST Microwave Studio, caractéristique de radiation.

ملخص:

أصبح الجيل الخامس من تقنيات الهاتف المحمول تقنية واعدة ومهمة ومتطورة في أنظمة الاتصالات اللاسلكية لكل من الاهتمامات الأكاديمية والصناعية. ومع ذلك، فإن أداء هذه الأنظمة يتأثر بشكل كبير بمجموعة واسعة من العوامل، مثل الطقس وتأثيرات المسارات المتعددة وتصميم هوائي فعال. ونتيجة لذلك، سيؤدي تحسين وابتكار تكوينات الهوائيات حتما إلى رفع مستوى الأداء العام لأنظمة الاتصالات اللاسلكية، كما يمكن أن يمهد الطريق لتطبيقات جديدة. تظهر الأبحاث الحديثة أن المواد الجديدة والمواد الخارقة ذات الميزات الفريدة ستمكن الهوائيات من أن تكون أصغر بكثير وأكثر مناعة ضد التداخل.

الهدف من هذه المذكرة هو التحقيق وتصميم هوائي متعدد الخدمات مليمتر لتطبيقات الجيل الخامس. يجمع المشروع بين العمل النظري والمنهجي والمفاهيمي، مما يؤدي إلى تصميم وتحسين مصفوفة microstrip، والتي يتردد صداها عند تردد28 جيجا هيرتز. يتم اقتراح بلورة ضوئية لتعزيز الاتجاه والمكاسب المحققة لتصميم الهوائي. يجب أن تحقق مصفوفة microstrip مع بلورة ضوئية مكاسب عالية وعرض نطاق ترددي عالٍ في كلا نطاقي التشغيل.

لقد صممنا هوائيين لتطبيقات الجيل الخامس باستخدام برنامج التصميم CST ، وهي منخفضة التكلفة للإنتاج وسهلة التصنيع لتطبيقات الجيل الخامس. تم عرض ومناقشة النتائج التي تم الحصول عليها حول أهم خصائص الهوائي، مثل فقدان الإرجاع ونمط الإشعاع والمكاسب ونسبة الموجة الدائمة (VSWR) للهوائي.

الكلمات المفتاحية : الجيل الخامس(5G)،نطاق المليمتر،مصفوفة هوائيmicrostrip patch ،الكريستال الضوئي، CST Microwave Studio ،خاصية الإشعاع.

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LIST OF ABBREVIATIONS:

1G: First-generation wireless mobile communication system

2G: Second Generation of Wireless Mobile Systems

3G: Third generation wireless mobile communication

4G: Fourth Generation of Wireless Communication

5G: Fifth Generation Mobile and Wireless Networks

ADC: Analog to Digital Converter

AMPS: Advanced Mobile Phone System

AVA : Antipodal Vivaldi Antenna

BSC: Base Station Controller

BTS: Base Transceiver Station

EDGE: Enhanced Data Rates for GSM Evolution

eMBB: Enhanced Mobile Broadband

FDMA: Frequency Division Multiple Access

FM: Frequency modulation technique

GMSK: Gaussian Minimum-Shift Keying

GPRS: General Packet Radio Service

IEEE: Institute of Electrical and Electronics Engineers

IoT: Internet of Things

LTE: Long Term Evolution

ME: Magneto-Electric

MIMO: Multiple Input Multiple Output

mMTC: Massive Machine-Type Communications

MSA: Microstrip Antenna

OFDMA: Orthogonal Frequency Division Multiple

NOMA: Non Orthogonal Multiple Access

PIFA: Planar Inverted-F Antenna

PSK: Phased Shift Keying

QoS: Quality Of Service

RF: Radio Frequency

SIM: Subscriber Identity Module

TACS: Total Access Communication System

TDD: Time Division Duplex

TDMA: Time Division Multiple Access

UMTS: Universal Mobile Telecommunications System

uRLLC: Ultra-reliable and Low Latency Communications

WiMAX: Worldwide Interoperability for Microwave Access

UCs: Unified Compting system

ICT: Information and Communication Technology

PhC: Photonic Crystal

GENERAL INTRODUCTION

A few decades ago, there has been a remarkable development in the field of wireless communications. This development is due to the growing demand for data rate, the transportable nature of the terminal, and the encumbrance of spectrum resources. Older mobile systems are incapable of providing optimal responses to these demands. The fifth-generation (5G) of mobile communication is an evolving technology that adds new features and responds to future needs and concerns, allowing mobile networks to make massive advancements in terms of data transfer, response time, and adaptability to user needs, this fast development motivates researchers to advance communication technology, whether in the software or infrastructure sectors.

Furthermore, the design of antennas is regarded as a critical topic that requires the ongoing development of 5G and beyond wireless communication networks.

The microstrip patch array antenna is a common component in communications and radar applications because it comes in a wide range of models, can be planar or conformal, and can be fed via a variety of methods. Because of the advantages of these sorts of designs, the use of microstrip patch array antenna has increased in recent years. A microstrip patch array antennas come in a variety of shapes and can function in a variety of ways depending on the application.

Our goal is to design and simulate an antenna that operates in the 28 GHz millimeter-wave spectrum for use in 5G networks while achieving all of the major characteristics of recent wireless communication systems. As a result, we relied on antenna theory to determine the geometric parameters of our microstrip patch array antenna and used the CST software to simulate the proposed construction.

This manuscript is organized as follows:

The first chapter introduces the context and motivation for the current topic. The chapter begins with a discussion of the need to develop 5G technology for millimeter-wave. Furthermore, the challenges of using millimeter-wave bands for mobile communication are discussed in conjunction with low-frequency mobile technology.

The second chapter introduces the indispensable for antenna design and their characteristics.

The third chapter will focus on the design of a millimeter-wave antenna, as well as a discussion of the obtained results,

This work will be concluded by a general conclusion and future project prospective.

CHAPTER I

I.1 Introduction:

Wireless communication, particularly cellular systems, is one of the fastest-growing and most vibrant technological fields in the communication sector. In 2019, there are 5,623 million mobile phone users worldwide, with that figure predicted to rise to 7,690 million by 2027 [1].

When we look at the term Wireless communication in its literal sense, we can see that it is made up of two words: The first is communication, in which data is sent from a transmitter to a receiver. The transmitter and receiver can be located anywhere between a few meters (like a television remote control) and thousands of Kilometers using wireless communication (Satellite Communication). The second term is Wireless, which describes the transmission of data between two or more points without the Use of an electrical line.

A mix of cellular networks and mobile devices that communicate via the radio frequency spectrum (Wirelessly) enables cellular telephony, also known as mobile cellular telephony. Thousands of nodes make up a cellular network, which assists mobile device users. As technology progresses, mobile gadgets, like the television and the computer, become increasingly affordable and powerful.

I.2 Evolution of Wireless Communication Networks:

Mobile communication technologies have gone through several stages in the past few decades after the introduction of the first generation mobile network Due to huge demand for more connections worldwide, which is divided as shown in a figure I.1:

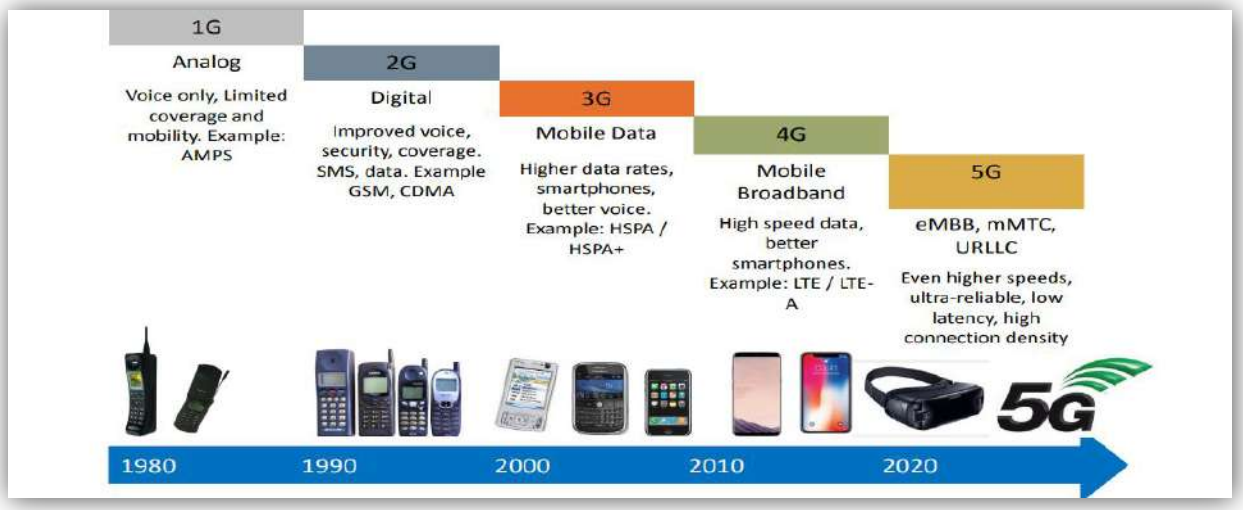


Figure I.1: Block diagram of the evolution of wireless network**[2]**.

I.2.1 Pre-cellular 0G:

The first wireless phone was the 0G, which became accessible after World War II. The mobile operator set up the calls in those pre-cell days, and there were only a few channels available [3].

Pre-cellular mobile telephony technology, such as radiotelephones that some people had in their automobiles is referred to as 0G before the arrival of cell phones [3].

I.2.2 0.5G technology:

0.5G refers to a set of technologies that are more advanced than the basic 0G technologies. These early mobile telephone systems differed from earlier closed radiotelephone systems in that they were offered as a commercial service on the public switched telephone network, with their phone numbers, rather than being part of a closed network like a police radio or taxi dispatch system [3].

I.2.3 First Generation of Mobile Communication Technology 1G:

The first generation of the wireless mobile communication system (1G) was introduced in 1980, it uses analog signals to transfer information, this information was only developed for voice at low speed [4]. This technology was based on the frequency modulation technique (FM) to process voice signals and Frequency Division Multiple Access (FDMA) [5].

Many first-generation communication systems existed:

- Advanced Mobile Phone System (AMPS) in the United States. It is located in the 800MHz band with a 30 kHz channel bandwidth and 10kbps data rate.
- Total Access Communication System (TACS) in Europe. It is located in the 900MHz frequency spectrum with a channel bandwidth of 25 kHz and a data rate of 2 kbps [6].

1G had poor voice quality due to interference, Poor battery life, large sized mobile phones, and less security, which led to the development of the second generation of wireless networks [7].

I.2.4 Second Generation of Mobile Communication Technology 2G:

The Second Generation of Wireless Mobile Systems (2G) is Deployed in France in the 1990s.The biggest change was using digital modulation instead of analog techniques, 2G allows for the addition of Short Message Service SMS to voice calls, as well as an increase in the voice call quality. Mobile phones have also become much smaller and more secure, It is based on the two techniques of digital multiple access technologies such

as Time Division Multiple Access (TDMA) and Code Division Multiple Access CDMA. The system can support a huge number of users [8].

I.2.4.1 GSM:

One of the most important features of the Global System for Mobile Communications (GSM) system is the Subscriber Identity Module (SIM) card. The GSM network is divided into three parts: the Mobile Station, the Access Network, which includes the Base Transceiver Station (BTS) and the Base Station Controller (BSC), and the Core Network [5].

It is located on 900 and 1800 MHz frequencies with low data transmission rates of less than 65 Kbytes/sec [6].

I.2.4.2 GPRS:

The General Packet Radio Service (GPRS) standard is an evolution of the GSM standard also called 2.5G. GPRS had a throughput of up to 85 kilobits per second with a maximum theoretical bit rate of 171.2 Kbits/s, which corresponds to a speed of approximately 115 Kbits/s for the end-user under optimal conditions with the same frequencies as GSM [8].

I.2.4.3 EDGE:

The next step in the evolution of the GSM standard was the Enhanced Data Rates for GSM Evolution (EDGE) standard, which provided data transmission rates up to three times faster than GPRS. AT&T introduced EDGE, also known as 2.75G. To support GSM, EDGE core networks do not need to make any hardware or software changes. The addition of a higher modulation technique of Phase-Shift Keying (8-PSK) to the Gaussian Minimum-Shift Keying (GMSK) modulation in GPRS is the key of this technology [5].

I.2.5 Third Generation of mobile communication Technology 3G:

In 2000, the third generation of a wireless mobile communication system (3G) was released. Increased data rates from 144kbps to 384kbps in wide coverage regions and 2Mbps in local coverage areas were the goals of 3G systems. In comparison to 1G and 2G, 3G provides its consumers with more advanced services such as services, access to TV/videos, Web browsing, email, videoconferencing, paging, fax, and navigational maps are all included in addition to voice communication. It has a bandwidth of 850-2100 MHz and used for high-speed internet, videoconferencing, and other applications [7].

The most common 3G technology is the Universal Mobile Telecommunications System (UMTS).3.5Ghas a similar network structure to 3G but offers fast data transmission rates in

the theory of around 14.4 Mbps for downlink and 5.76 Mbps for uplink but in practice, this speed was around 200 Kbps for uplink and 500 Kbps of the downlink [4].

I.2.6 Fourth Generation of Mobile Communication Technology 4G:

The Fourth Generation of wireless communication, known as 4G started in 2010.4G networks is an enhanced version of IEEE's 3G networks, with higher data rates and the ability to handle more advanced multimedia services, it allows its users to connect to the internet at extremely fast speeds. The 'Open Wireless Architecture' of 4G systems enables multiple wireless air interfaces in an open architecture platform, resulting in ultra-high spectral efficiency and data transmission rates of 100 Mbps to 1Gbpswith a coverage range of 10 to 50 kilometers [4].

There are two different 4G networks. The Worldwide Interoperability for Microwave Access (WiMAX) technology and Long Term Evolution (LTE).LTE is a fully packet-switched network based on Internet Protocol IP with assured Quality of Service (QoS) classes, it uses Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple Input Multiple Output (MIMO) techniques [9].

I.2.7 Fifth Generation of Mobile Communication Technology 5G:

The Fifth Generation Wireless Systems (5G) is a term used to describe wireless communication technologies that aim to increase network capacity by providing consumers with faster networks and very high data rates for multimedia streaming. Millimeter waves were employed to achieve this in high frequencies. Much advancement in antenna designs has been made to serve smart phones and 5G mobile base stations. The new 5G antennas will work at high frequencies and have a bandwidth of more than 1 GHz. A major goal of 5G systems with lower costs and more coverage is to increase the capacity of wireless networks. The majority of contemporary wireless communications research has focused on the high-frequency bands. As a result, compact antenna diameters appropriate for use in mobile smart phones are produced. Furthermore, array arrangements are required for 5G antennas to attain high gain. 5G systems will also enable MIMO (multiple input multiple output) technologies. The data rate of 5G systems will be more than 1Gbps. In comparison to earlier generations, 5G systems offer quicker data transmission, more capacity, improved video and audio clarity, and interactive multimedia capabilities [6].

It is used across three main types of connected services:

● **Enhanced mobile broadband (eMBB):** It had something to do with human-centric and expanded access to multimedia content, services, and data, as well as improved performance and a more seamless user experience. This service type, which can be seen as an evolution of the services currently provided by 4G networks, covers UCs with a wide range of requirements, such as hotspot UCs with high user density, very high traffic capacity, and low user mobility, to wide-area coverage cases with medium to high user mobility, but the need for seamless radio coverage virtually anywhere and anytime with visibly improved user data rates compared to today [10].

● **Ultra-reliable and low-latency communications (URLLC):** It had to do with UCs that had severe standards for latency, dependability, and availability. Wireless control of industrial manufacturing or production processes, remote medical surgeries, smart grid distribution automation, transportation safety, and so on are examples. URLLC services are predicted to be a key component of the fourth industrial revolution (commonly referred to as Industry 4.0) and have a significant impact on industries other than information and communication technology (ICT) [10].

● **Massive machine-type communications (mMTC):** capturing services with a high number of connected devices that normally communicate a little amount of non-delay sensitive data However, Logistics applications (e.g., including the monitoring of tagged products), smart metering, or agricultural applications (where small, low-cost, low-power sensors are sprinkled over huge regions to detect ground humidity, fertility, etc.) are all examples of this service type [10].

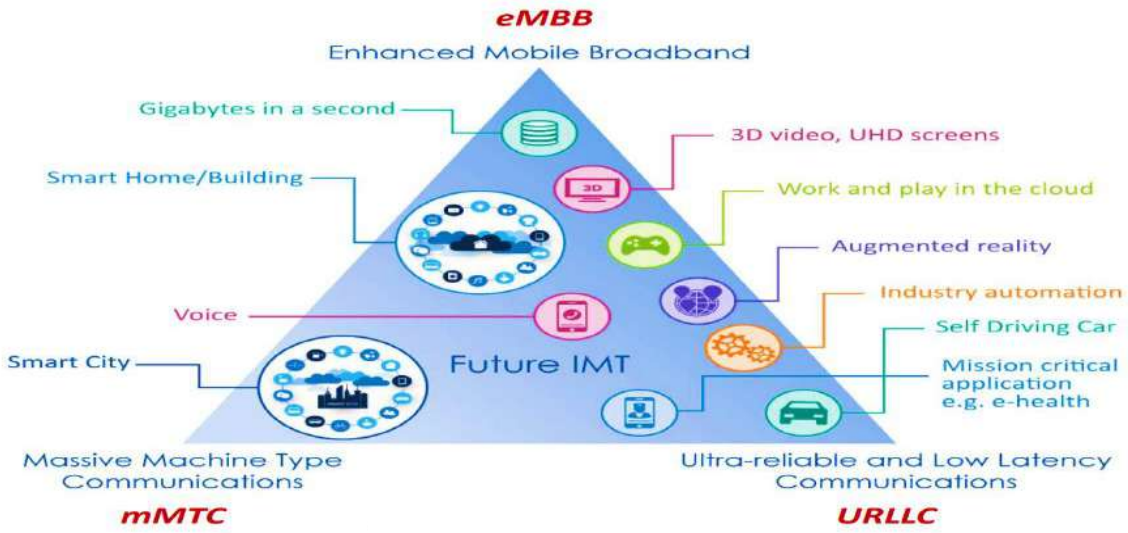
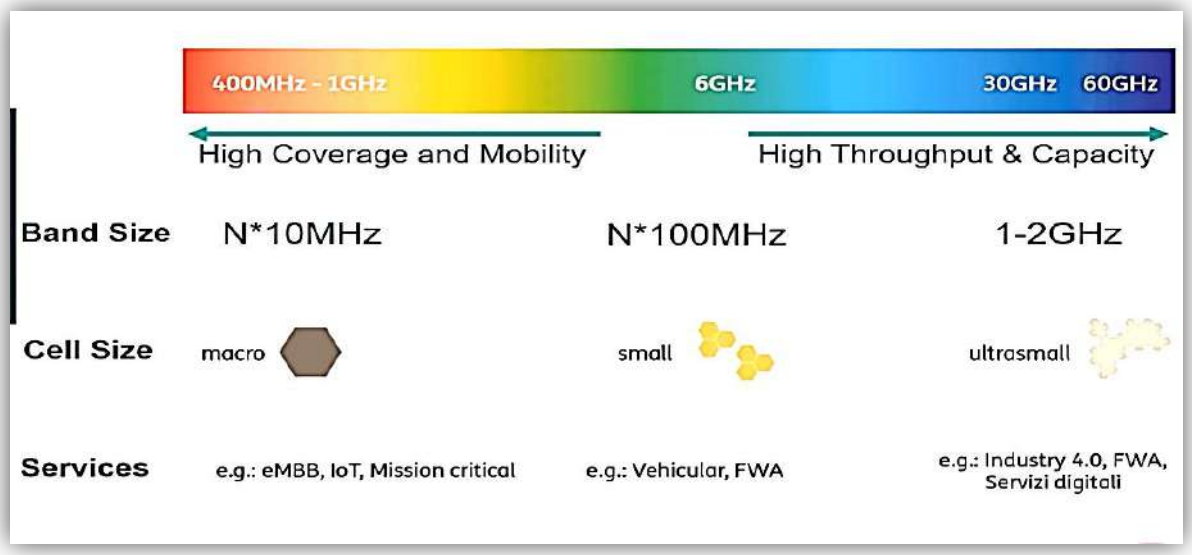


Figure I.2: Three generic 5G services emphasizing different 5G requirements **[11]**.

I.1 5G frequency bands:

The 5G frequency range is divided into two bands: 410 MHz to 7125 MHz and 24.25 GHz to 52.6 GHz [12]. As a result, the smaller the device, the greater the coverage and mobility, but the lower the capacity and speed. The band size for low frequencies is around orders of 10 MHertz, for 6 Hertz it is an order of 100 MHz, and for millimeter waves it is one to two GHz [13].



FigureI.3: Band size, Cell size, and Services of 5G.

I.2 Internet of Things (IoT):

The Internet of Things (IoT) is a term that refers to a network of connected devices. The Internet of Things (IoT) is a new and exciting technology that has the potential to change the world by connecting real objects. The Internet of Things has taken the interest of the research community, with the ultimate goal of connecting wearable, health care, smart cities, vehicle automation, environment, and other entities to a common interface with the ability to communicate with one another. Alsohas an implication for every industry, including finance, retail, and manufacturing [14].

I.2.1 IoT advantages and disadvantages:

Internet of things facilitates the several advantages in day-to-day life in the business sector is to Access to information from any location, at any time, on any device, and Improved communication between electronic devices that are connected also the Task automation improves the quality of a company's services while reducing the need for human

intervention Alternatively, it is estimated that there are approximately one million square kilometers [14].

As the Internet of things facilitates a set of benefits, it also creates a significant set of challenges like the number of linked devices grows and more information is shared between them, the risk of a hacker stealing personal data grows as well Enterprises may someday have to deal with a large number of IoT devices, possibly millions, and collecting and managing data from all of those devices will be difficult and If the system contains a problem, every linked device is likely to become corrupted [14].

I.3 Massive MIMO antenna technology (M-MIMO):

MIMO is a smart antenna design that employs multiple antennas at both base stations and terminals. MIMO has mostly been investigated and used to boost the capacity of cellular and broadband systems. MIMO has been used in 4G LTE networks in many configurations. In LTE networks, a 2 ×2 MIMO system are often employed, which refers to two transmit antennas at the base station and two receive antennas at the device. The 4× 4 and 8× 8 configurations result in a base station with four/eight transmit antennas and four/eight reception antennas also MIMO in LTE enables more reliable transmission of data. It separates the data into individual streams before transmission [15].

Large-scale antenna systems, very large MIMO, hyper MIMO, and full-dimension (FD) MIMO are some of the various names given to Mimo in 5G. It can have tens of antennas on both ends, earning it the moniker "massive MIMO." It can also called "large scale MIMO." Thomas L. Marzetta was the first to proposethis idea in 11-2010 [15].

Massive MIMO is a form of a communication system in which the base station (BS) comprises hundreds of antenna arrays that serve users in the tens of the same time-frequency resource to improve this data rate to 20 Gbps or more. The benefit of such a system is that the BS with multiple antennas may send separate data streams to many users; this aids the attainment of a large data rate. Additionally, using massive MIMO improves network reliability, coverage area, and energy efficiency [16].

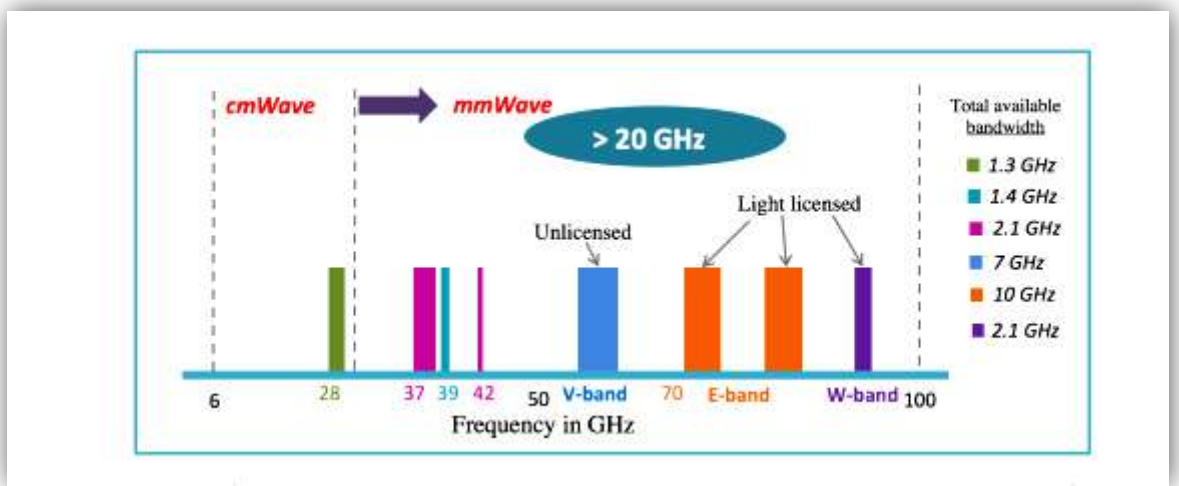
I.4 M-MIMO in Millimeter-wave:

The Millimeter-wave spectrum has been used traditionally for a variety of reasons. Because of its high radio propagation losses, mm-Waves are unsuited for traditional cellular macro base stations where coverage is a major concern. Furthermore, the considerable

bandwidth available in the mm-Wave spectrum was unnecessary. Keep in mind that mm-Wave operation is more expensive than lower frequencies [17].

The available spectrum at mm-Wave, on the other hand, is an attractive feature for 5G ultra-dense networks. Furthermore, the need for enormous cell densification in 5G networks transforms mm-Wave's propagation characteristics into a benefit by increasing radio spectrum re-usability. In the case of 5G M-MIMO, because mm-Wave frequencies have a tiny wavelength, a large number of antenna elements may be built in small arrays, making M-MIMO easier to realize and execute [17].

Millimeter waves are electromagnetic (radio) waves that typically have frequencies between 30 and 300 GHz. As shown in Figure I.4, the millimeter-wave band has a wavelength range of 10 mm at 30 GHz and 1 mm at 300 GHz [17].

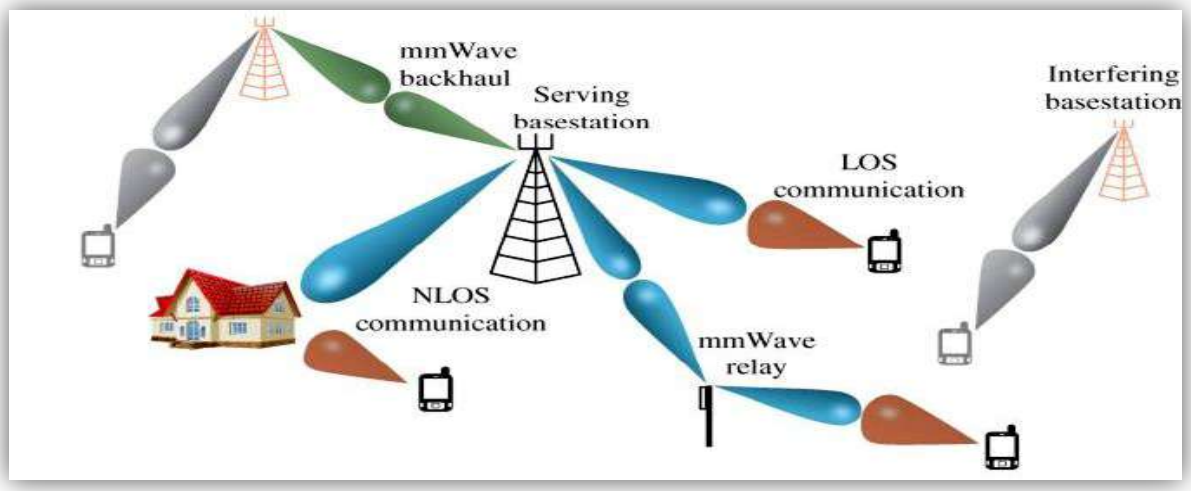


FigureI.4: Available bandwidth in the mm-wave spectrum **[18]**.

I.4.1 The architecture of Millimeter-wave:

In 4G networks, the entire geographical area is divided into cells, with one or more 4G base stations covering each cell. High directional antennas are used in mm-Wave transmission and reception, which helps to limit mutual interference between mm-Wave base stations[19].

The architecture of mm-Wave cellular networks is likely to be much different than in microwave systems, as illustrated in Figure I.5. High gain links between the base station and handset will arise from directional beamforming, which will reduce out-of-cell interference. As a result, aggressive spatial reuse may be possible. Backhaul lines, for example, might share the same mm-Wave spectrum, allowing for quick deployment and mesh-like connectivity through base station cooperation [19].



FigureI.5: Illustration of an mm-Wave cellular network **[20]**.

Mobile backhaul is the connection between the base stations because there is little interference among mm-Wave concurrent channels, directed mm-Wave communication links can called pseudo-wired [19].

I.4.2 Millimeter-wave advantages:

Millimeter-wave is one of the most important inventions because it ensures many advantages, which are:

- Antenna sizes are very small and hence large numbers of antennas are packed in a small area. As a result, millimeter wave technology is being employed to increase capacity [21].
- Mm-waves provide more security and privacy [21].
- As a result, higher data rates are achieved [21].
- Due to more bandwidth in the millimeter range, it is more favorable for smaller cell deployment [21].

I.4.3 Millimeter-wave disadvantages:

On the other hand, although a Millimeter-wave is useful however it has limitations, which are:

- At extremely high frequencies, the Millimeter-wave goes through different losses such as penetration, rain attenuation, Oxygen…etc. This reduces the mm wave's distance coverage requirement in 5G cellular mobile deployments [21].

- Smaller component sizes necessitate more manufacturing precision, which contributes to higher costs [21].
- Smaller antennas in a receiving system receive less energy, reducing sensitivity [21].

I.5 Full Duplex:

Transceivers are used in today's base stations and cell phones, which must take turns broadcasting and receiving information on the same frequency, or function on various frequencies if a user wants to transmit and receive data at the same time. In 5G, A transceiver will be able to send and receive data on the same frequency at the same time theoretically doubling the system's throughput over half-duplex systems. Full duplex is a technique that has the potential to increase wireless network capacity [22].

On the contrary, FD allows a device to send and receive signals at the same time on the same frequency, resulting in improved Spectrum Efficiency also The tests have shown that full-duplex can improve auto-interference cancellation by more than 113 dB in actual situations, resulting in a 90 percent increase in system throughput over traditional half-duplex modes. Furthermore, in this figure, the desired signals are represented as straight black lines, while the transmit and receive antennas of an FD device are denoted as Tx and Rx respectively [22].

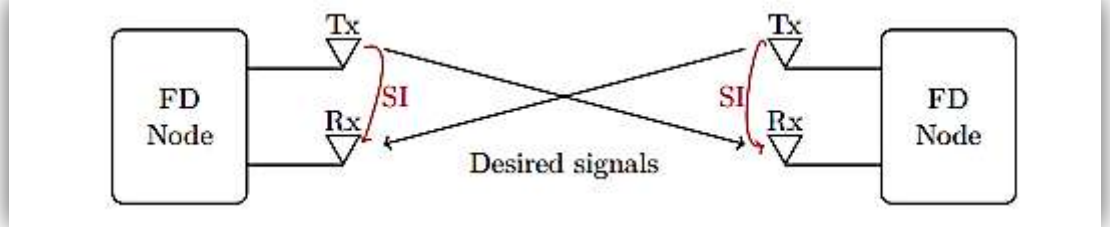


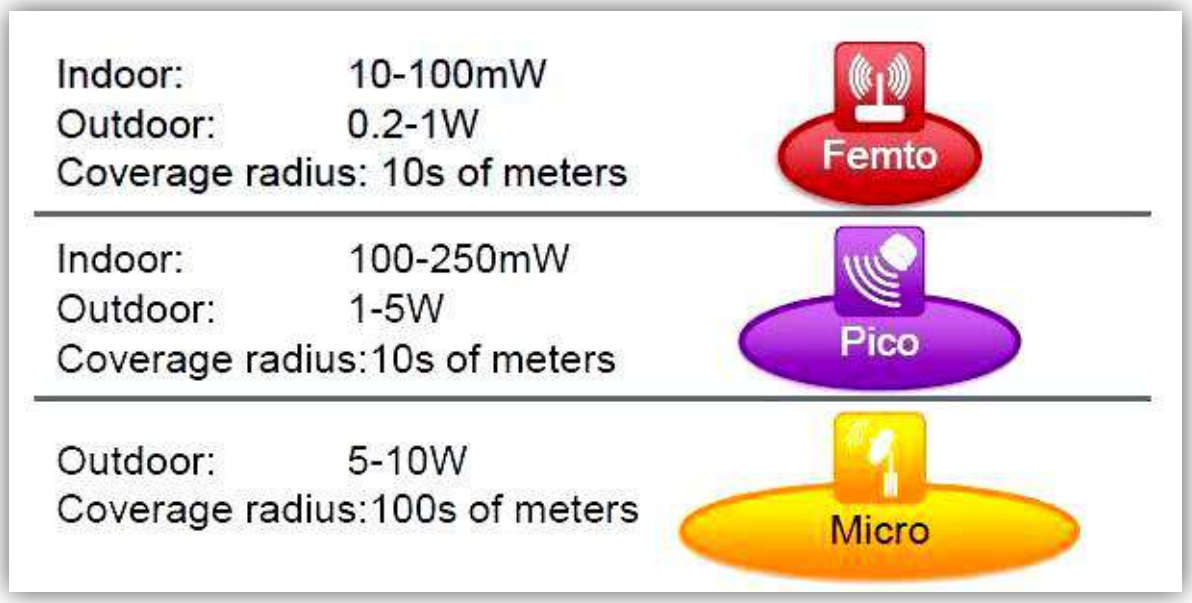
Figure I.6: A model of full-duplex peer-to-peer communication.**[22]**.

I.6 Small cell:

As networks have matured and data traffic demands have risen exponentially, the idea of providing localized resources, more mobile users, and more required data by filling coverage gaps and maintaining service quality through small cell deployments has proven to be an appealing solution, allowing operators to better track traffic demands and use spectrum resources more efficiently, resulting in increased network capacity. Small cells are low-power wireless access points that operate in the permitted spectrum. They are operator-managed to improve cellular coverage, capacity, and applications for homes and businesses, as well as in

urban and rural public spaces with the IoT challenges although small cells use short-range BSs [23].

Small cells come in a variety of coverage profiles, broadly increasing in size from femtocells (the smallest) to macro cells (the largest) and power characteristics, as shown in figure I.7:



FigureI.7: The variety of coverage profiles of small cells**[24]**.

Small cells are also an important component of Heterogeneous networks (HetNet) which aim to deliver more capacity and increased spectrum efficiency while decreasing the cost–per–bit of transporting data [23].

I.7 Orthogonal and Non-Orthogonal Frequency Division Multiple Accesses:

The role of OFDMA remains strong with 5G, similar to what it was with LTE. In a sense, it is even stronger as now and used also in the uplink direction, in addition to the single carrier transmission. With 5G, the single carrier transmission is only intended to be used at the cell edge when there are limitations with the link budget, otherwise, OFDMA is used. The usage of OFDMA is motivated by improved performance in the situation of multiple antenna transmission. Interference management in Time Division Duplex (TDD) networks is another consideration. If both the uplink and downlink use the same multiple access solution, this is easier to manage.

Non Orthogonal Frequency Division Multiple Accesses (NOMA) are fundamentally different from these multiple access schemes that provide users with orthogonal access in time, frequency, code, or space. In NOMA, each user operates in the same band at the same time, distinguished only by their power levels [12].

I.8 Beamforming:

The use of the microwave and millimeter-wave (mm-Wave) frequency bands for fifth-generation (5G) communication technology, applications such as the Internet of Things requires antenna beamforming technology. It can be defined as the ability of an antenna array to steer the maximum radiation toward a prescribed direction [13].

Multiple antennas are spatially collocated to either serve as an independent radiator or as a single cell in larger array arrangements to enable beamforming. Because it also includes numerous antenna systems, the term multiple-input–multiple-output (MIMO) has recently been used in conjunction with beamforming technology, tying the two together [13].

In which emitted energy from an antenna array can be directed towards a specific spatial sector and if properly built, would prevent from traveling in directions where the radiated signal is not required. A beamformer is a system that performs this function. As we move from one communication system to the next, the needs and development problems for beamformers change. As a result, beamformers could be classified into:

I.8.1 Analog beamformer:

As shown in figure I.8, it is the simplest beamforming architecture. It only uses a single Radio Frequency (RF) chain consisting of an Analog to Digital Converter (ADC) and a mixer (up/down converter)[25],this means that each antenna element can only produce one beam at a time. The data stream is split into as many signal paths as there are antenna elements, and each signal path is supplied by a phase shifter (responsible for steering the beam.) The phase of each element is controlled by advanced technology and sent to the appropriate antenna element. Analog beamforming improves the gain of the antenna array, allowing for greater coverage [26] and [27].

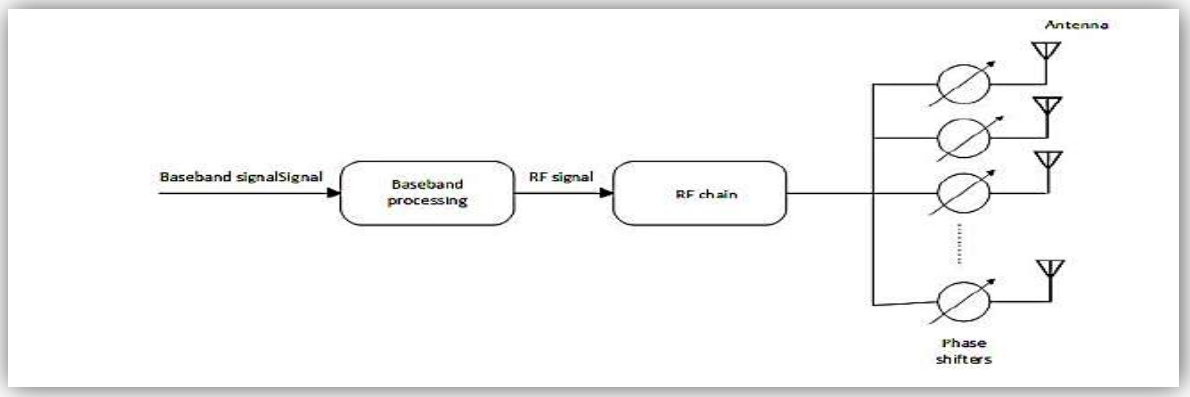


Figure I.8: Analog beamforming scenario **[27]**.

The advantage of the analog beamformer is its simple implementation and cost reduction. On the other hand, one RF chain can transmit only one stream at a time [27].

I.8.2 Digital Beamformer:

In this approach, each antenna element has its transceiver and data converters, as shown in Figure I.9. Each antenna element has its own RF chain and phase shifter, implying that each antenna element has its own RF chain and phase shifter. This enables the generation and application of a large number of signal sets to the antenna elements. The antenna array can handle several data streams and create multiple directed beams at the same time. Because this antenna can emit several beams, it can send data to multiple receivers at the same time, effectively serving multiple users [26][27].

With digital beamforming, different sets of signals can be produced and superimposed onto the antenna array elements, allowing a single antenna array to serve many beams and hence multiple users. Although this flexibility is advantageous for 5G networks, digital beamforming requires more hardware and signal processing, resulting in higher power consumption, particularly at mm-Wave frequencies, where hundreds of antenna components are possible. A multi-beam MIMO technique is possible with digital beamforming. It is best suited for base stations rather than mobile devices because of its complexity and high hardware cost [26][27].

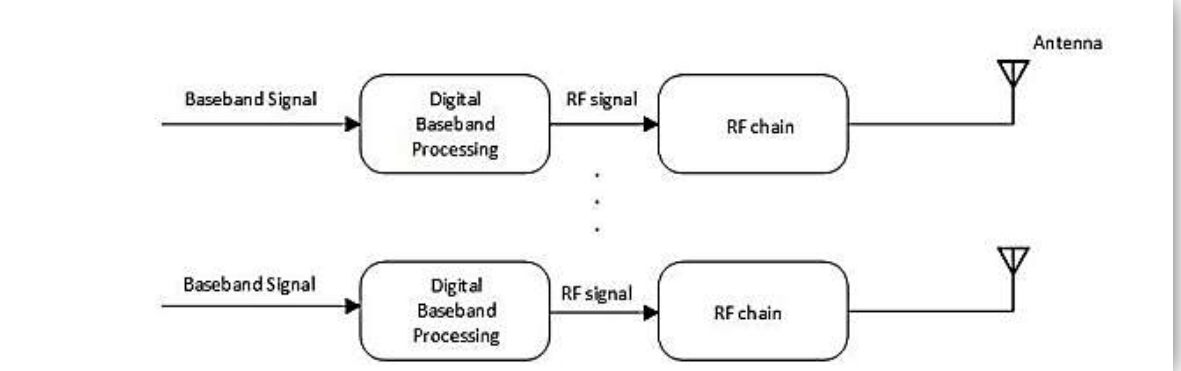


Figure I.9: Fully digital beamforming scenario **[27]**.

Before we pass to hybrid beamforming, we present in Table 1 a comparison between digital and analog beamforming .

Table1: Comparison of digital and analog beamforming **[28]**.

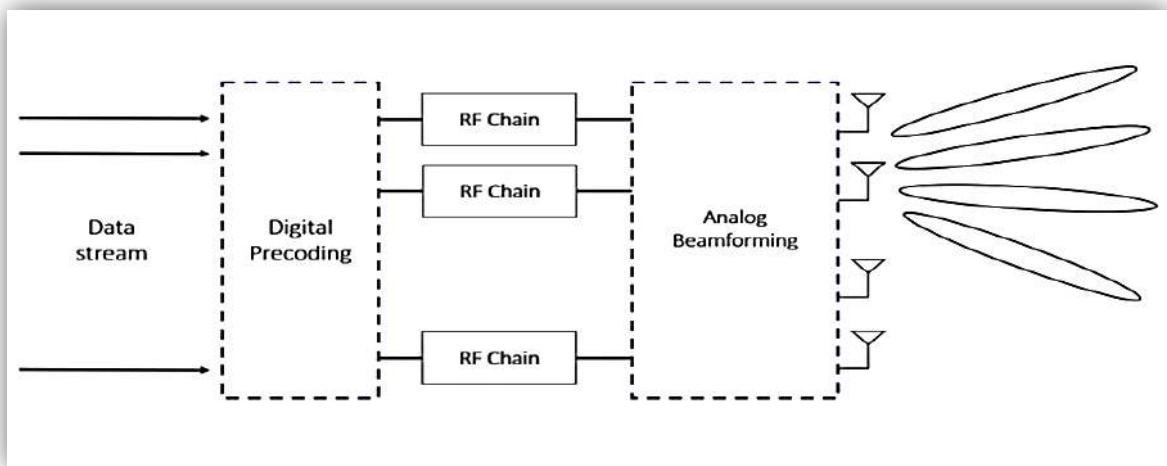
Beamforming	Degree of freedom	Implementation	complexity	Power consumption	Cost	Inter-User interference	Data streams
Digital	High	ADC/DAC Mixer	high	High	High	Low	multiple
Analog	Low	Phase shifter	low	Low	Low	High	Single

I.8.3 Hybrid or analog/digital Beamformers:

The interference cancellation quality is inferior to that of a digital beamformer. Connecting each antenna element to a digital domain, on the other hand, necessitates complicated hardware configurations. These considerations led to the development of a beamformer topology that aims to combine the advantages of both digital and analog beamforming. An analog/digital or hybrid beamformer is the name given to such a beamformer [12].

In a beamforming antenna, the number of TRXs (i.e transceiver (TRx) is a device that can transmit and receive signals) can be less than the number of antenna elements. Digital processing in the baseband is used for part of the beamforming, and analog RF beamformers are used for the rest. This method is known as hybrid beamforming. Digital beamforming necessitates the use of a specialized RF chain for each antenna element. The goal of hybrid beamforming is to reduce the number of RF chains in the beamforming antenna, lowering its

cost and complexity. Figure I.10 shows hybrid beamforming in action. At the 3.5 GHz band in urban microcells [12].



FigureI.10: Hybrid beamforming concept **[29]**.

The big changes in comparison with previous technologies are beamforming and massive MIMO resulting in small antenna sizes required because the millimeter wave (MM wave) spectrum, uses highly directive beamforming antennas.

I.9 The types of 5G Antennas:

The following are some examples of antennas that are appropriate for 5G applications:

- **Magneto-Electric (ME) Dipole Antenna:** It is made up of a vertically shorted planar magnetic dipole and a planar electric dipole. The magnetic dipole is fed from the bottom side of the substrate. It is characterized by a high front-to-back ratio, low side lobe and back lobe level, wide bandwidth, and low cross-polarization but the design and fabrication of this type of antenna are complex and expensive [30][31].
- **Loop Antenna:** It is made up of a ring that is circular, rectangular, square, or any other form. The loop antenna's radius is lower than the wavelength. This type is easy to design, provides wider bandwidth, and gives a stable radiation pattern. Because a single-element loop antenna will not fulfill the 5G requirements, a multi-element loop antenna is necessary. So the profit goes down [32][33].
- **Antipodal Vivaldi Antenna (AVA):** it comprises two conductors that are mirror copies of each other on both sides of the substrate. The upper conductor serves as a radiator, while the bottom conductor serves as a ground. It enhances the gain, provides

wider bandwidth, and gives a stable radiation pattern. This antenna requires more space and low gain at lower frequencies [34][35].

- **Planar Inverted-F Antenna (PIFA):** It is made up of a patch antenna and a ground plane that is linked with a shorting pin and fed from the substrate's bottom side. It has a quarter wavelength resonance that requires less space, low profile, good impedance matching, and enhances front to back ratio but this antenna offers narrow bandwidth and low gain [36][37].
- **Microstrip Antenna (MSA):** It consists of three parts; the first is the metal radiating patch that is hung over the dielectric substrate, which is the second half of the MSA. The ground plane, which is constructed of the same metal as the patch layer and is hung underneath the substrate, is the last component. It has many advantages when comparing it with other antenna types such as Inexpensive and easy to fabricate, small size, and thin shape, it supports linear and circular polarization their feeding methods are easy and require no cavity backing with the capability of dual and triple frequency operations [38].

When comparing microstrip antennas with other conventional antennas, we find optimal results in all the parameters, these antennas can perform a multiband operation. We can also use a microstrip antenna array. This is the subject of this dissertation [38].

CHAPTER II

II.1 Introduction :

An antenna is defined by Webster's Dictionary as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves." The IEEE Standard Definitions of Terms for Antennas (IEEE Std 145–1983) defines the antenna or aerial as "a means for radiating or receiving radio waves [39]".

The antenna is one of the most important components in wireless systems. An antenna is a device that transmits or receives electromagnetic waves. It turns electrical currents into electromagnetic waves (transmitting antenna) and vice versa (receiving antenna). The shape and the size of antennas are based on their applications and operating frequency [40].

In other words, the antenna is the transitional structure between free space and a guiding device, as shown in figure II.1:

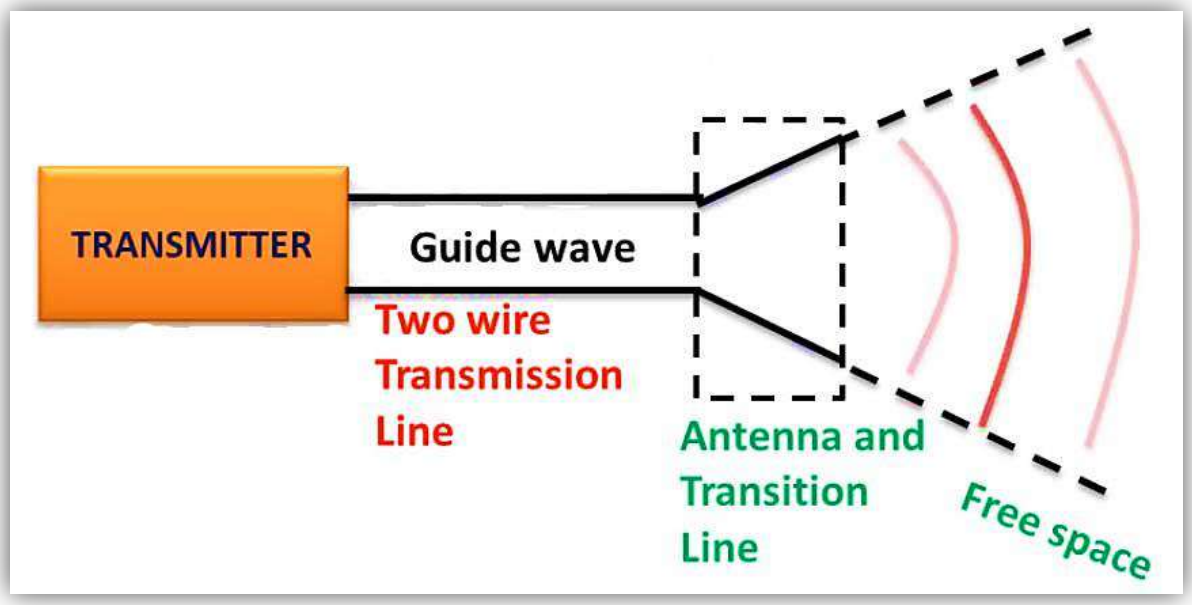


Figure II.1: Antenna as a transition device**[41]**.

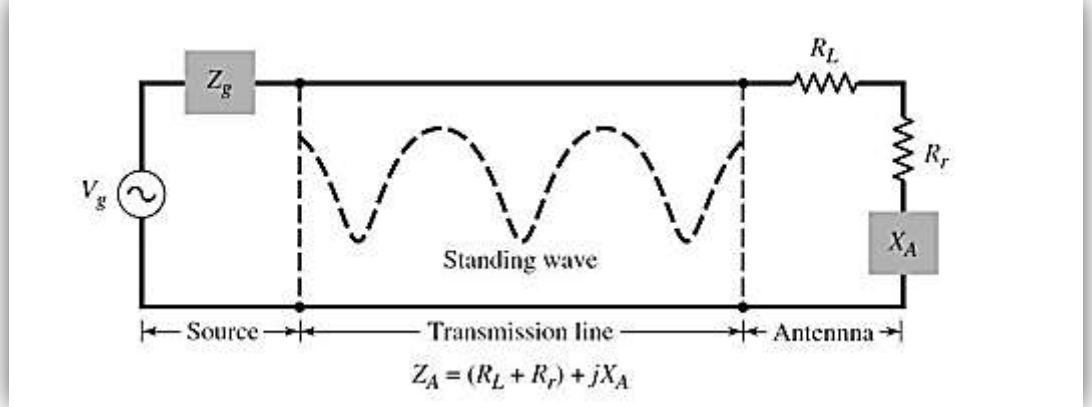
The guiding device or transmission line may take the form of a coaxial line or a hollow pipe (waveguide), and it is used to transport electromagnetic energy from the transmission source to the antenna or from the antenna to the receiver [39].

In addition to receiving or transmitting energy, an antenna is an advanced wireless system that is usually required to optimize or accentuate the radiation energy in some directions and suppress it in others. It must then take various forms to meet the particular need at hand, and it

may be a piece of conducting wire, an aperture, a patch, an array, a reflector, a lens, and so forth [39].

As shown in Figure II.2, the antenna systems can be represented in Thevenin equivalent Circuit, where an ideal generator represents the source, a line with characteristic impedance $Z_c$represents the transmission line, and a load Z_A represents the antenna.

In this ideal case, we aim to transform all the source energy into radiation resistance.



FigureII.2: Antenna Thevenin Equivalent **[39]**.

II.2 Fundamental Parameters of Antenna:

II.2.1 ReturnLoss (S11) :

Antenna return loss measures the power delivery efficiency from a transmission line to an antenna. If the incident power is Pin and the reflected power is Pref, then the ratio Pin/Pref shows the degree of mismatch between the two powers. Either the return loss is expressed in terms of the return signal in decibels or VSWR present on the input to the antenna. Return loss is given by [42][43]:

$$\text{RL (dB)} = 10log_{10}\frac{p_{in}}{p_{ref}} \qquad (2.2)$$

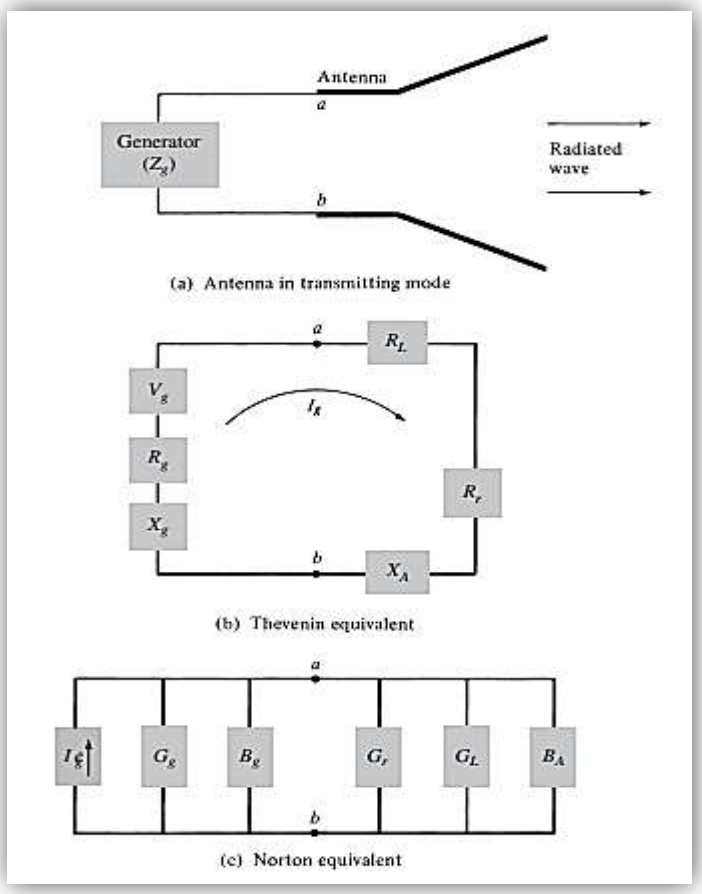
II.2.2 Bandwidth:

The bandwidth of an antenna is defined as "the range of frequencies within which the performance of the antenna, concerning some characteristic, conforms to a specified standard». It can be considered as the range of frequencies over which important performance parameters are acceptable [39].

II.2.3 Input Impedance:

Antennas will never use as stand-alone devices; we will have to consider antennas as being part of a system. Therefore it need to know the impedance characteristics of the impedance presented by an antenna at its terminals or the ratio of the voltage to current between two terminals or the ratio of the appropriate components of the electric to magnetic fields at a point [39][40].

When looking into the antenna, at the antenna terminals, we may regard the antenna as complex impedance Z_A



FigureII.3: Transmitting antenna and its equivalent circuits **[40]**.

In Figure II.3 (a) these terminals are designated as a−b. The ratio of the voltage to current at these terminals, with no load attached, defines the impedance of the antenna as [39][40]:

$$Z_A = R_A + jX_A \qquad (2.3)$$

Where:

Z_A ,R_A and $X_A$is antennaimpedance, resistance, and reactance at terminals a–b (ohms) respectively.

RA consists of two components given by [39][40] as follows:

$$R_A = R_r + R_L \qquad (2.4)$$

Where:

$R_r$is the radiation resistance of the antenna and R_L is the loss resistance of the antenna

II.2.4 Directivity:

The directivity of an antenna is defined as "the ratio of the radiation intensity U in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power P_{rad}radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied." Stated more simply, the directivity of a non-isotropic source is equal to the ratio of its radiation intensity U in a given direction over the radiation intensity U0 of an isotropic source. In mathematical form, it can be written by [44] as fellow:

$$D=\frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \qquad (2.5)$$

Where:

D is Directivity, U and U_0 are Radiation Intensity of the designed and the isotropic antenna respectively with P_{rad} is Total radiation power.

II.2.5 Antenna Efficiency:

The antenna radiation efficiency is defined as the ratio of the total radiated power to the power accepted by the antenna at the input. The mismatching between the antenna causes the losses in the power and the transmission line, the losses affecting the antenna radiation efficiency can be of both conductive and dielectric nature [45].

$$\text{Efficiency } (\eta) = \frac{Radiatedpower\ (P_{rad})}{Inputpower\ (P_{input})} \qquad (2.6)$$

II.2.6 Gain:

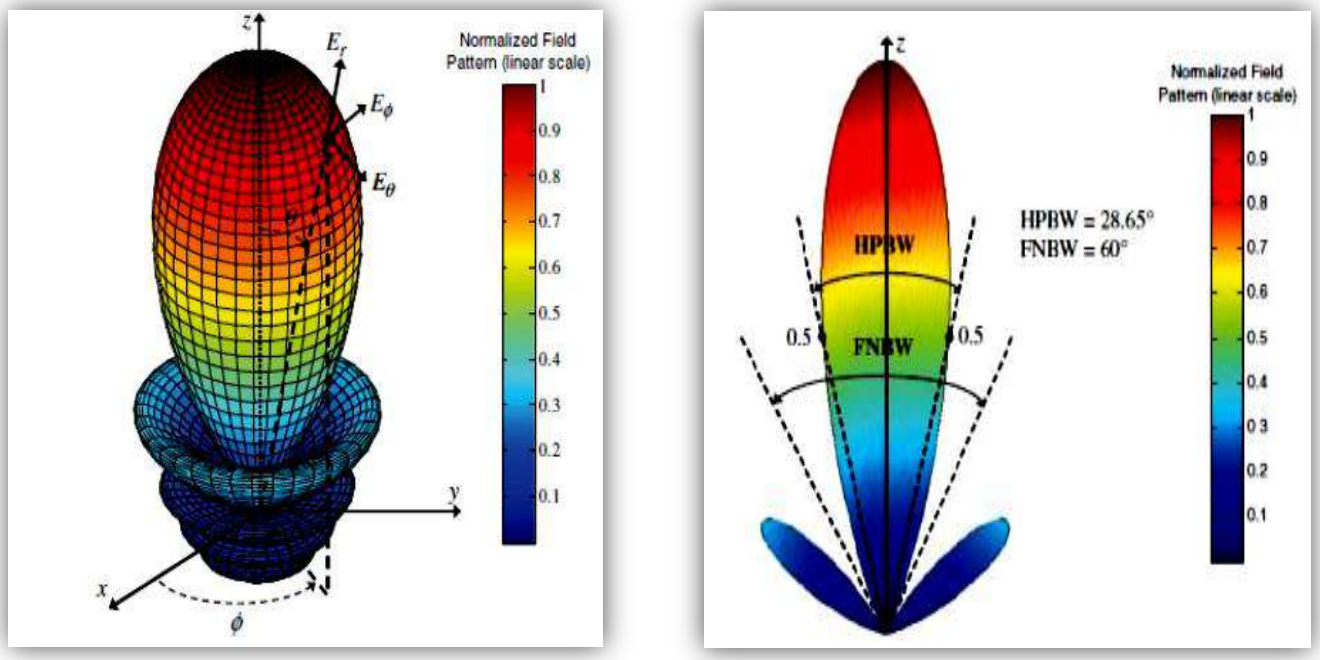
The gain of the antenna is closely related to the directivity**,** Gain is expressed relative to an isotropic radiator or sometimes a half-wavelength dipole[39].

Gain of an antenna is defined as “the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically [39]”.

$$\text{Gain} = 4\pi \frac{radiation\ intensity}{total\ input\ (accepted) power} \qquad (2.7)$$

II.2.7 Beam-width :

The beam-width of a pattern is defined as the angular separation between two identical points on the opposite side of the pattern maximum. In an antenna pattern, there are several beam-widths. One of the most widely used beam-widths is the Half-Power Beam-width (HPBW),There is another important beam-width which is the First Null Beam-width (FNBW) that is defined as the angular separation between the first nulls of the patterns [39].



FigureII.4: Three- and two-dimensional power patterns in linear scale**[39]**.

II.2.8 Polarization:

The polarization of an electromagnetic wave follows the direction of the electric field. Therefore, we can define the antenna polarization as the polarization of the transmitted waves

from the antenna in the designed direction. When the direction is not stated, the polarization is taken to be the polarization in the direction of maximum gain [40][44].

We can define antenna polarization as the polarization of the transmitted waves from the antenna in the designed direction. Polarization may classify as:

- **Linear Polarization:** The antenna is then linearly polarized. When the phase difference is 0◦ or 180◦. the time-phased difference between the two components is given by [44]:

$$\Delta\varphi = \varphi y - \varphi x = n\pi,\ n = 0, 1, 2, 3, \cdots \qquad (2.8)$$

- **Circular Polarization:** can be achieved only when the field components are equal in amplitude and the phase difference is plus or minus 90◦. That is [44]

$$|Ex| = |Ey| \Rightarrow Ex_0 = Ey_0 \qquad (2.9)$$

$$\Delta\varphi = \varphi y - \varphi x = +(1/2+2*n)\pi,\quad n = 0, 1, 2, \cdots \qquad (2.10)$$

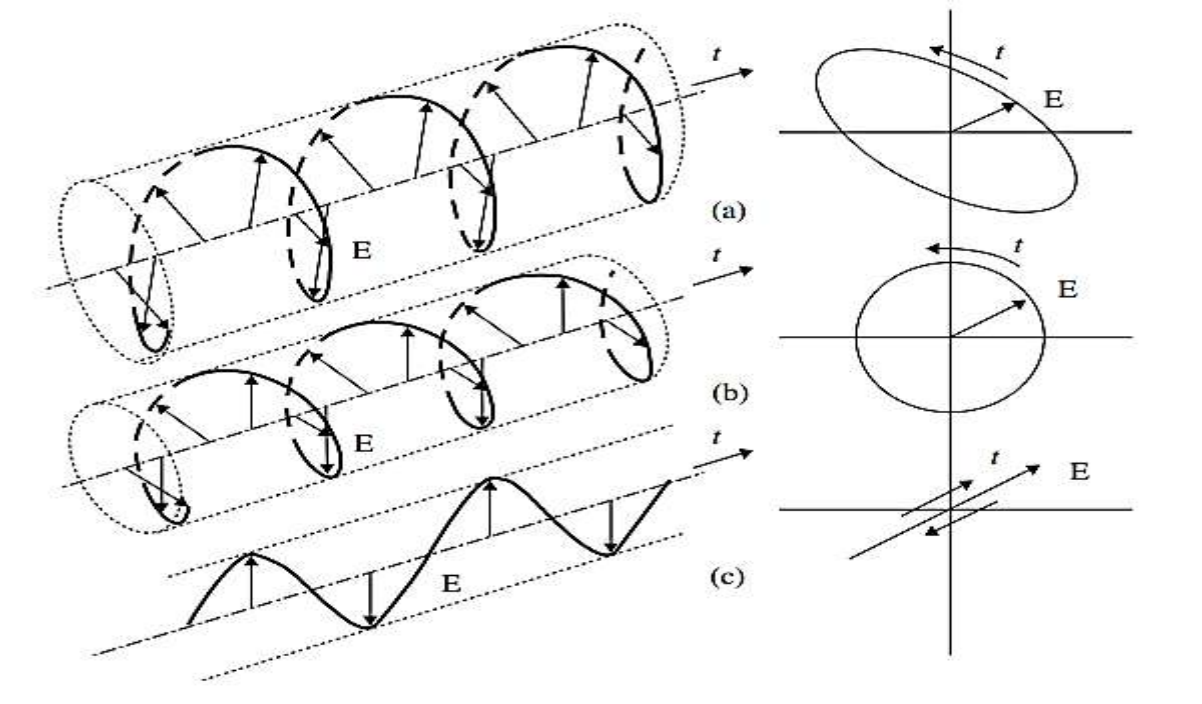
$$\Delta\varphi = \varphi y - \varphi x = -(1/2+2*n)\pi,\quad n = 0, 1, 2, \cdots \qquad (2.11)$$

- **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 the time phase difference between the two components is not equal to multiples of π/2. We can see that the linear and the circular polarization can be considered as a special case of the Elliptical polarization [44].

$$|Ex| = |Ey| \Rightarrow Ex_0 = Ey_0 \qquad (2.12)$$

$$\Delta\varphi = \varphi y - \varphi x = +(1/2+2*n)\pi,\quad n = 0, 1, 2, \cdots \qquad (2.13)$$

$$\Delta\varphi = \varphi y - \varphi x = -(1/2+2*n)\pi,\quad n = 0, 1, 2, \cdots \qquad (2.14)$$



FigureII.5: Polarization states.(a) Elliptical polarization.(b) Circular polarization.(c) Linear polarization.**[40]**.

II.2.9 Voltage Standing Wave Ratio (VSWR) :

It is a measurement of the source's reflected power, it's computed by comparing the forward voltage wave toward the load to the reflected voltage wave from the load.

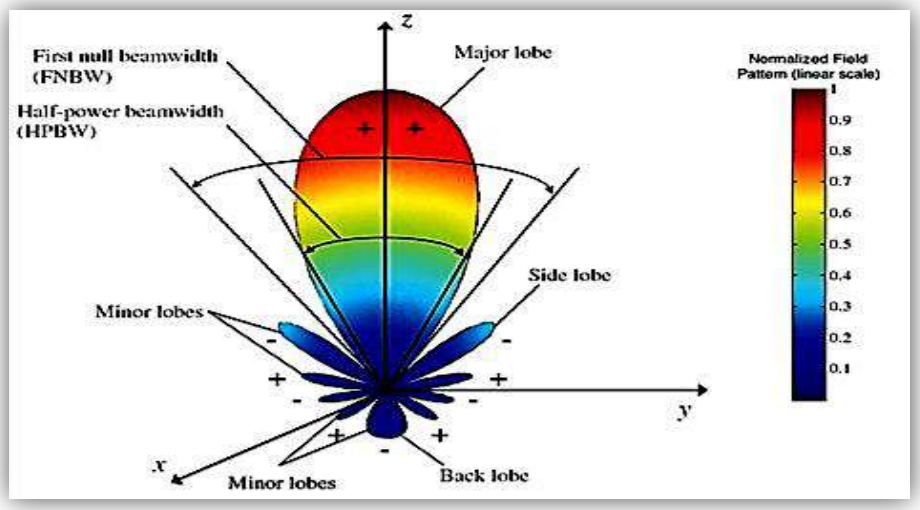
An ideal VSWR signifies the ratio of 1:1. The VSWR value is usually 2:1. That is, 88.9% of the energy sent to the antenna by the transmitter is radiated into free space and 11.1% is either reflected into the source or lost as heat during the transmission process. Return loss is also used as the statistics to measure the bandwidth of the antenna [42][43].

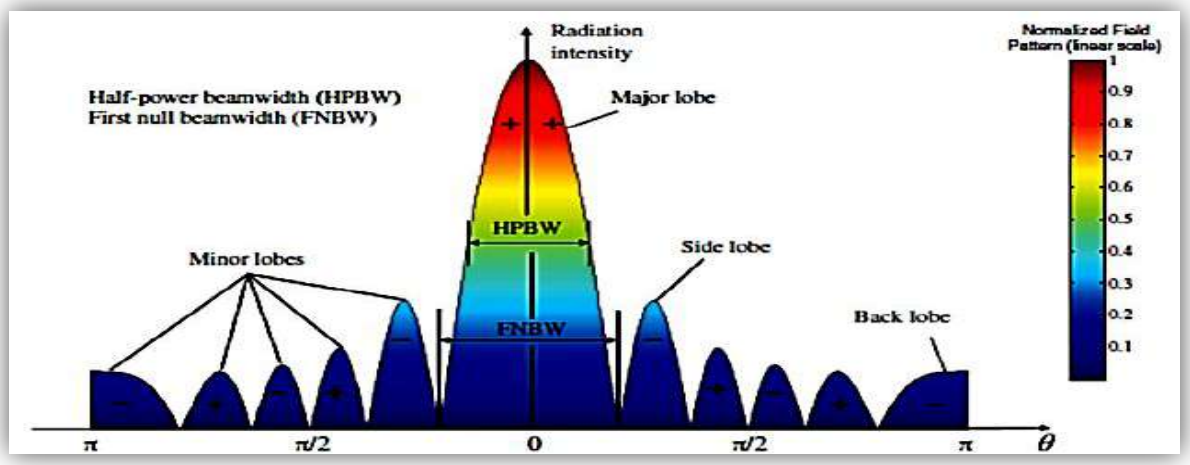
II.2.10 Radiation Pattern :

An antenna radiation pattern is defined as "a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates". In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase, or polarization [39].

The radiation property of most concern is the two three-dimensional spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius [39].

Various parts of a radiation pattern are referred to as lobes, which may be sub-classified into major (main) and minor (side, and back) lobes. The figure II.6 demonstrates an asymmetrical three-dimensional polar pattern with a number of radiation lobes. Some are of greater intensity than others, but all are classified as lobes [44].





FigureII.6: Radiation lobes and beamwidths of an antenna pattern and linear plot of power pattern and its associated lobes and beamwidths**[44]**.

A major lobe, also called the main beam, is defined as "the radiation lobe containing the direction of maximum radiation." In Figure II.6 the major lobe is pointing in the θ = 0° direction [44].

A minor lobe is any lobe except the major lobe (back or side lobe),it usually represents radiation in undesired directions, and they should be minimized [44].

A side lobe is "a radiation lobe in any direction other than the intended lobe." (Usually a side lobe is adjacent to the main lobe .they are normally the largest of the minor lobes [44].

A back lobe is "a radiation lobe whose axis makes an angle of approximately 180° for the main beam of an antenna"[44].

There are three Radiation pattern types depending on the direction of the radiation: Isotropic Which is the radiation pattern of an ideal antenna, and Omni-directional Some antennas (such as dipoles, loops, and broadside arrays) exhibit Omni-directional patterns, as illustrated by the three-dimensional antenna which has equal radiations in a given plane and directional radiations in any orthogonal plane and the last is Directional which has effectively radiation in some directions than other directions [46].

II.3 Antenna Arrays:

An array antenna is formed by combining similar or different types of antennas and work as one array antenna. It is not required to link similar parts together, but it is preferable for ease of construction. Array antenna, antenna array, or array is the name given to the combination of all the parts. A radiation beam with a small beam width can be formed by placing similar pieces at regular intervals on a line (linear array antenna), in a plane (planar array antenna), or in (a conformal array) [40].

II.3.1 Concept of Antenna Arrays :

An array is made up of several identical antennas that are fed with certain amplitudes and phases to produce the desired radiation pattern. It is possible to alter not only the primary beam direction but also the side lobe properties, using this technology. In an array, gain and directivity are also improved. As a result, arrays are especially appealing for space communications, as they require exceptionally high gain and narrow beams (high directivity) [47].

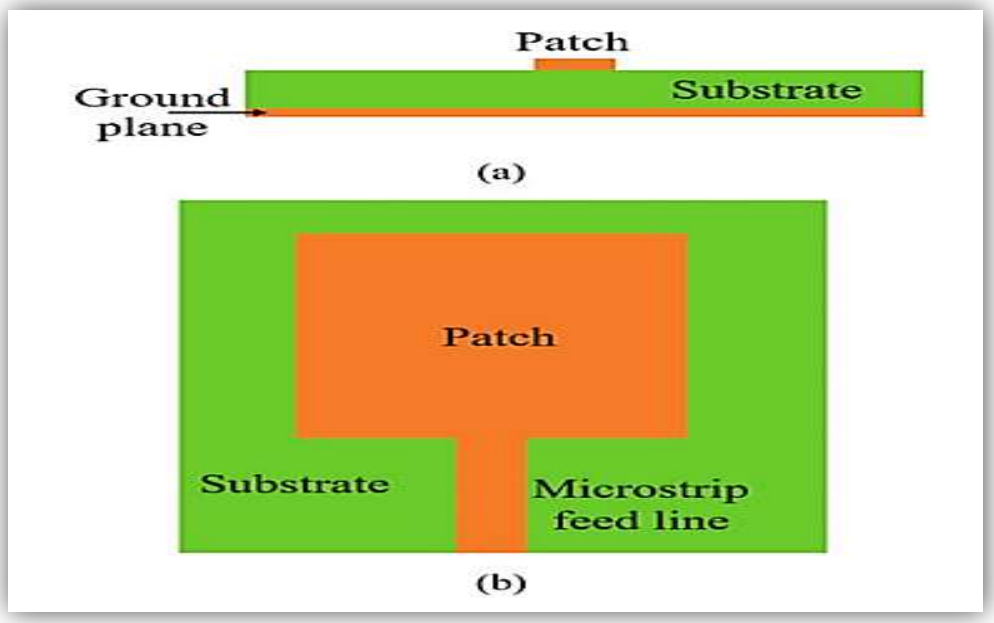
The Major Advantages of Antenna Arrays according to [48] are:

- Increase gain: the array gain is N times the elements gain if we ignore the coupling between N items of an array.

- To shape the radiation pattern (beamforming and beam stirring): the radiation pattern can be reconfigured both in terms of maximum radiation direction.
- The microstrip array antenna has many possible configurations.
- Provide diverse reception.
- Determine the direction of arrival of the incoming signals.

II.4 Microstrip patch antenna:

In the 1970s, microstrip patch antennas became increasingly popular, mainly for space applications. Now, they are employed for both government and commercial purposes. These antennas consist of a metallic patch, a ground plane, and a dielectric substrate. The metallic patch can take many different configurations, (rectangular, circular, square, triangular, dipole, elliptical...) the rectangular is the most popular as shown in Figure II.7 because of its attractive radiation characteristics ease of analysis and fabrication [49].



FigureII.7: Rectangular microstrip patch antenna: a side view، b top view [43].

FigureII.7 shows the ground plane and a patch, respectively, are the lowest conducting surface and the higher conducting plate. The antenna's patch and ground plane are connected to a supply line known as the microstrip feed line. The supply to the antenna is provided via a variety of feeding mechanisms [49].

The mathematical equation of the resonance frequency is given by the following equation:

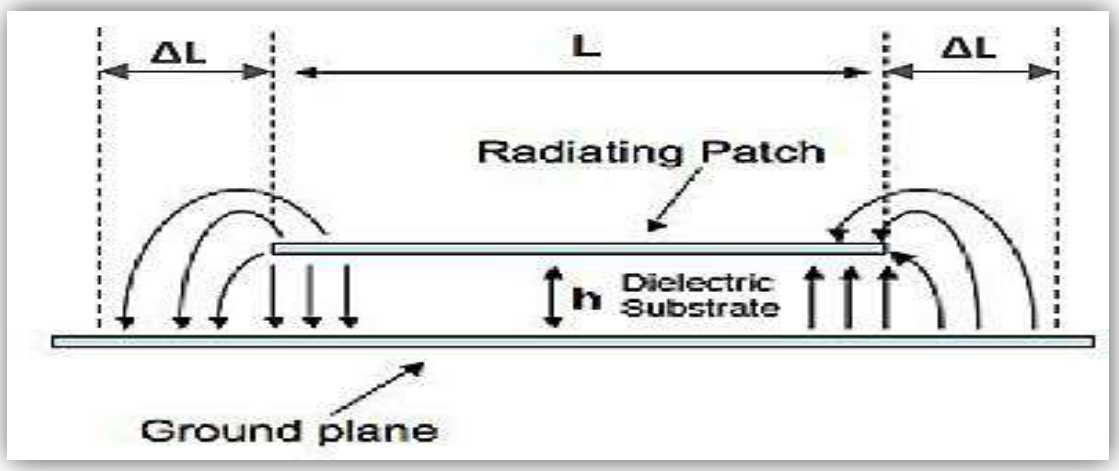
$$f_0 = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \qquad (2.15)$$

The width (W) of the rectangular patch antenna is calculated as:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \qquad (2.16)$$

Where:

C is the speed of light in free space, $f_0\ is$ Operating frequency, and $\varepsilon_r\ is$ Permittivity constant of a dielectric substrate.



FigureII.8: Fringing field lines of the microstrip antenna **[49]**.

When the feed line excites the patch, a charge distribution is established on the ground plane and the patch's underside. The feed excitation negatively charges the ground plane and positively charges the patch. Between the ground plane and the patch, attractive forces are created, resulting in fringe fields. This fringing effect is the same as extending the patch by ΔL distance [50].

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{w}{h}+0.8)} \qquad (2.17)$$

- The effective dielectric constant:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{-\frac{1}{2}} \quad (2.18)$$

Where :

ε_r and h is permittivity and thickness of substrate .

- The effective length:

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \quad (2.19)$$

- The patch length:

$$L = L_{eff} - \Delta L \quad (2.20)$$

- Calculation of the width of the feed line:

The width of the microstrip feed line can be discovered after determining the equation according to the conditions

$$U = \frac{W_F}{h} \quad (2.21)$$

Where :

W_F is the width of microstrip feed line

$$\frac{W_F}{h} = \frac{8e^A}{e^{2A-2}} \quad (2.22)$$

Where the value A is determined by the equation:

$$A = \frac{z_0}{100}\left[\frac{\varepsilon_r+1}{2}\right]^{0.5} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left[0.23+\frac{0.11}{\varepsilon_r}\right] \quad (2.23)$$

- Calculation of the Length of Feed Line :

It can be determined by the equation:

$$L_F = \frac{1}{4}\lambda_g \quad (2.24)$$

Where:

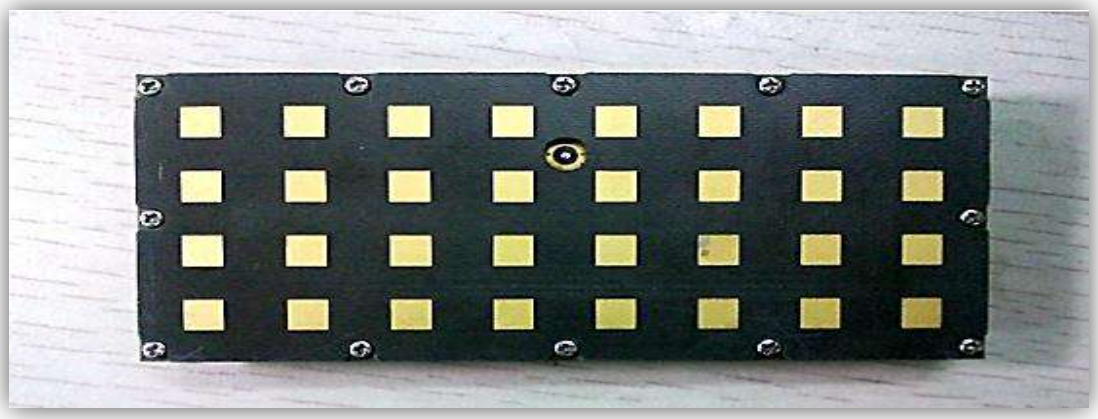
L_F is length of feed line and λ_s wave length of substrate and it has a relation with wave length in air (λ_0) and effective dielectric constant(ε_{eff}) as shown in the following equation :

$$\lambda_s = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \qquad (2.25)$$

II.5 Microstrip patch array antenna:

Microstrip antenna array are often chosen when the thin, conformal nature of these antennas is valued, in an antenna array; the signals of all individual elements are coordinated to achieve better antenna directivity, gain, and SNR over those of a single antenna.

The main limitation of microstrip is that it radiates efficiently only over a narrow band of frequencies and they can not operate at the high power levels of a waveguide, coaxial line, or even strip line [42].



FigureII.9: Microstrip patch array **[51]**.

Microstrip array geometry can be linear, planar, or conformal, and the feed system can be parallel, series, or hybrid, as with an array. Several feeding network configurations can be used depending on the array geometry [52].

II.6 Feeding Network:

II.6.1 Series Fed Arrays:

The series fed array was one of the early microstrip patch array implementations. A set of transmission cables connects each element of the array in series [39][53].

The single elements of the patch antenna array are fed by a single feed line where each patch feeds from the previous one. Figure II.10 shows a schematic diagram of an 8-element series fed array consisting of edge-fed patches. The array is fed from the left and is classified as a standing wave array [39][53].

This technique is limited to arrays with a fixed beam or those which are scanned by varying the frequency, but it can be applied to linear and planar arrays with single or dual polarization also any change in one of the elements or feed lines affects the performance of the others [39][53].

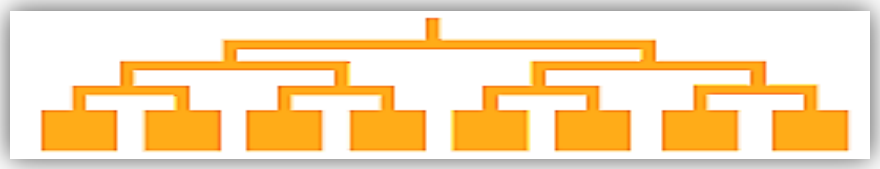


FigureII.10: Series Feeding**[54]**.

II.6.2 Corporate (Parallel) Feeding:

The most common type of array using microstrip patch technology is parallel (corporate) fed microstrip patch arrays. With this method, the designer has more control of the feed of each element (amplitude and phase) and it is ideal for scanning phased arrays, multi-beam arrays, or shaped-beam arrays because of the ability to change the feeding lines lengths separately. This means that the corporate feed array can have the gear-steering capability for the antenna radiation patterns [39][53].

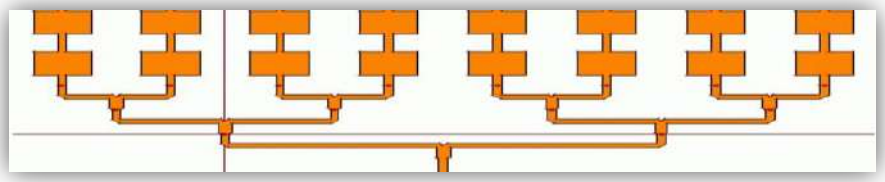
Figure II.11 shows a schematic diagram of an 8- element corporate feed array of edge-fed microstrip.



FigureII.11: Corporate Feeding**[54]**.

II.6.3 Series-Corporate Feeding:

As illustrated in Figure II.12, it is a hybrid of the two prior approaches [39][53].



FigureII.12: Series-Corporate Feeding**[54].**

II.7 Surface wave:

Many antenna designs produce surface waves as a by-product. Surface waves diminish antenna efficiency and gain by directing electromagnetic wave propagation along the ground plane rather than into free space. Surface wave diffraction increases back lobe radiations, which can degrade the signal-to-noise ratio in wireless communication devices like GPS receivers. They can also cause unintended coupling between array components [55].

The dielectric constant $\varepsilon_r$and the thickness h of the substrate determine the phase velocity of the surface wave. Surface wave excitation in a dielectric slab backed by a ground plane has been extensively researched (Collin, Field Theory of Guided Waves). There is no cut-off frequency in the lowest-order TM mode,TM_0. The cut-off frequencies for the higher-order modes (TM_nandTE_n) are given by [56]:

$$f_c{}^{(n)} = \frac{n*c}{4h\sqrt{\epsilon_r - 1}}\text{, n=1, 2 …} \qquad (2.27)$$

Where:c is the vacuum speed of light. The odd n = 1, 3, 5... Determines the cut-off frequencies for TM_n modes, while the even n determines the cut-off frequencies for TM_n modes [56].

The electromagnetic band gap (EBG) structures band gap property has been proven to be useful in suppressing surface waves in various antenna designs. To boost the antenna gain and lessen the back lobe, an EBG structure is used to surround a microstrip antenna [55].

II.8 Photonic Crystals:

Photonic crystals (PhCs) are a new type of optical media made up of natural or man-made structures with periodic refractive index modulation. Such optical media offer some unique qualities that enable a variety of applications to be constructed on its foundation [57].

II.8.1 Fundamental Principles of Photonic Crystal:

Photonic crystals are a type of photonic material having a spatially periodic dielectric constant distribution. The photonic band gap effect, which arises from the modulation of light by a spatially periodic distribution of dielectric constants, is one of the photonic crystal's distinctive features [59].

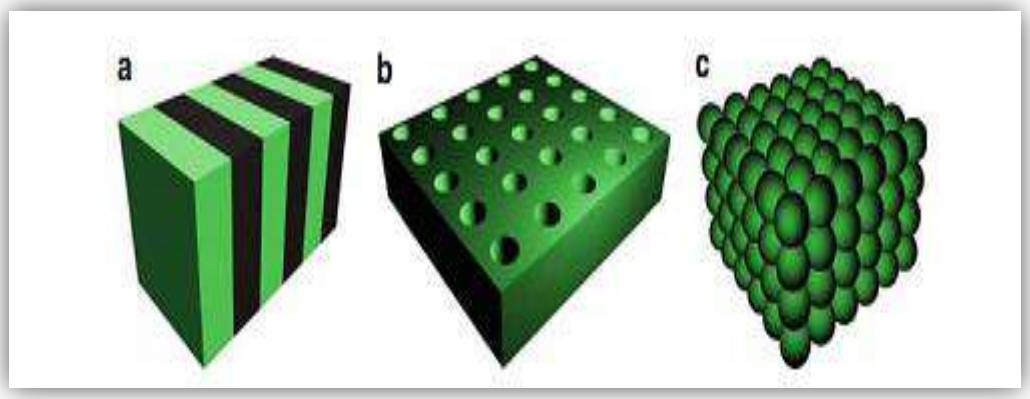
Artificial photonic crystals are constructed of two (or more) types of dielectric materials that are regularly positioned in space. A photonic crystal's dielectric distribution fluctuates regularly in space, creating a "periodic potential" for electromagnetic waves entering the photonic crystal. In the interfaces of distinct dielectric components, electromagnetic waves experience intense coherent scattering [60].

Photons are a great transporter of information. The advantages of photons include their vast data storage capacity and fast data transfer speed.

II.8.2 Types of photonic crystals:

PhCs are classified into three groups based on their geometry: one-dimensional (1D) structures were discovered in 1887. The dielectric constant of the photonic crystal varies in one direction, while two-dimensional (2D) and three-dimensional (3D) structures were not discovered until 1987.

Where the dielectric constant varies in two and three dimensions, respectively in Figure II.13 shows some examples.



FigureII.13: Examples of 1D, 2D and 3D photonic crystals (a) 1D PhC, (b) 2D PhC,(c)3D Phc**[57]**.

II.8.2.1 One-dimensional (1D):

The periodic modulation of permittivity occurs in one direction only in 1D PhCs, whereas the structure is uniform in the other two directions. The Bragg grating, which is frequently employed as a distributed reflector in vertical-cavity surface-emitting lasers, is an example of such a PhC. Furthermore, anti-reflective coatings, which allow for a significant reduction in surface reflectance and are used to improve the quality of lenses, prisms, and other optical components, are frequently used [57][58].

II.8.2.2 Two-dimensional (2D):

Because the permittivity of 2D PhC is periodic in two directions, while the medium is uniform in the third, it can have a surprisingly wide range of topologies. Porous silicon with periodically ordered pores, which is represented by the silicon substrate with etched holes, is a nice example of the 2D PhC. A periodically ordered system of dielectric rods in the air is another example of 2D PhC. In nature, 2D PhC can also be discovered. The rainbow play on the butterfly's wing, for example, is generated by light reflection from the microstructure on the wing [57][58].

II.8.2.3 Three-dimensional (3D):

Permittivity modulation occurs in all three directions in 3D PhC. When compared to 1D or 2D PhC, the number of conceivable PhC configurations is substantially bigger. Many works are devoted to the creation of novel geometric configurations for 3D PhC, to discover new applications for them. Valuable stone opal is the most well-known naturally produced 3D PhC. The remarkable optical qualities of this stone make it stand out. It changes colors when you turn it around [57][58].

II.8.3 Photonic Bandgap:

The photonic band gap, also known as the stopband, is the frequency range in which the density of photon states in photonic band structures is zero. The photonic crystal will reflect an incident electromagnetic wave with a resonance frequency that falls inside the photonic band gap. The reason for this is that the photonic crystal lacks equivalent Bloch modes that can propagate through it [61].

II.8.4 Characterization of Photonic Bandgap:

II.8.4.1 Dispersion Relation:

Solving the Maxwell equation can be obtained the dispersion relation of a photonic crystal .

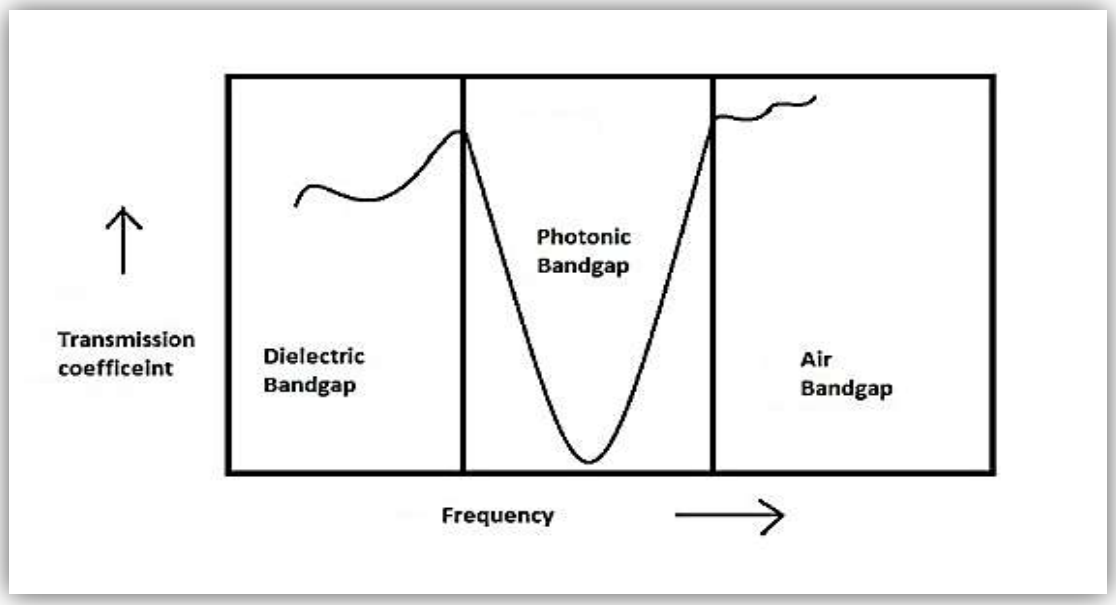
$$-\frac{\pi}{a} \leq k < \frac{\pi}{a} \qquad (2.28)$$

Where: (a) is the lattice constant for each wave vector (k).

The photonic band gap is a term used to describe the difference between two wavelengths of light. The electromagnetic variation theory predicts that electromagnetic modes with a high resonant frequency will concentrate their energy in the photonic crystal's low dielectric material area. While electromagnetic modes with a low resonance frequency will focus their energy on the photonic crystal's high dielectric material area. As a result, the dielectric band is also known as the passband under the basic photonic band gap. The air-band is the pass band above the basic photonic band gap [60].

II.8.4.2 Transmittance Spectrum:

The transmittance of the frequency range corresponding to a photonic band gap should be zero in the ideal scenario, whereas the transmittance of the pass bands should be 100%. As a result, a steep drop in the transmittance spectrum of a photonic crystal will occur. If we ignore the effect of intrinsic material absorption on the photonic band gap structure, we may calculate the position and breadth of the photonic band gap by using deep dips in the transmittance spectrum of a photonic crystal [60].



FigureII.14: The band gap Transmittance in a photonic crystal **[61]**.

II.8.4.3 Reflectance Spectrum:

The reflectance of the frequency range corresponding to a photonic band gap should be 100% in the ideal scenario, whereas the reflectance of the passbands should be zero. As a result, a high peak will emerge in a photonic crystal's reflectance spectrum. This correlates to the photonic bandgap's location [60].

If we ignore the effect of intrinsic material absorption on the photonic band gap structure, the position and breadth of the photonic band gap may be estimated by using high reflection peaks in the reflectance spectrum of a photonic crystal. Various simulation approaches to solve Maxwell equations have been devised to derive the photonic band gap structure of a photonic crystal [60].

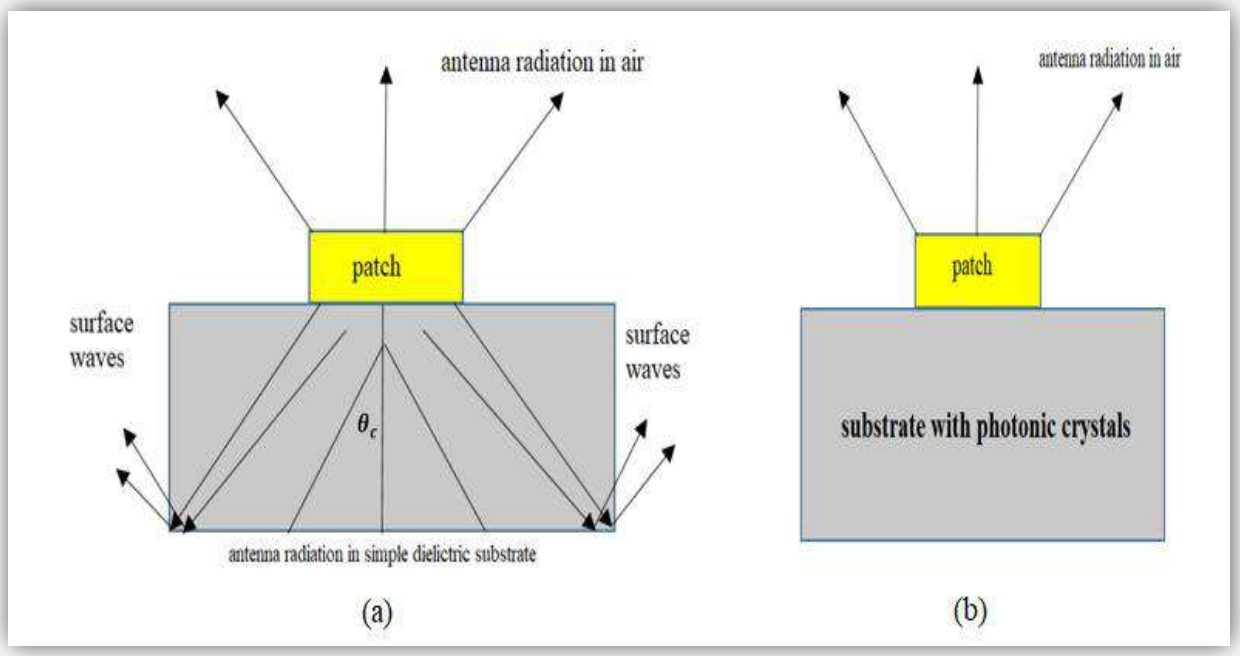
II.8.5 Photonic Crystal Substrates in Antennas:

Photonic crystals are low-loss periodic dielectric structures in which the photonic band gap is created using dielectrics with various refractive indices. For a particular range of frequencies, this photonic band gap acts as a stop-band filter, preventing them from propagating in certain directions [62].

The bandwidth of high dielectric constant substrates is limited. This can be improved by thickening the substrates. Unfortunately, this produces strong surface waves, reducing antenna

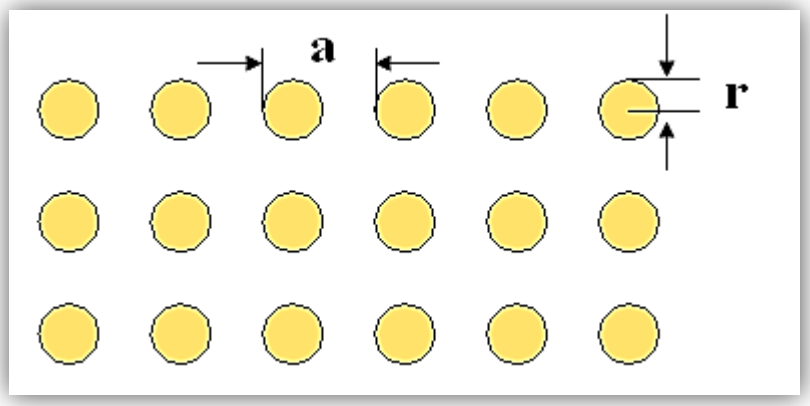
efficiency. Photonic crystals can be used to block surface waves, thereby resolving this issue. [63].

Comparison of primary microstrip patch antenna with and without photonic crystal shown in figure II.15:



FigureII.15:(a) simple antenna (b) Photonic Crystal antenna Substrates.

II.9 Characteristics of 2D Photonic Crystal:



FigureII.16: 2D photonic crystal.

Figure II.16shows the study of a two-dimensional photonic crystal manufactured by a periodic array of holes and structured in a rectangular lattice form. The mathematical representation is [64]:

$$E(r+a,t) = E(r,t)e^{ik.a} \qquad (2.29)$$

Where:

(a) Is lattice vector, (k) is wave vector, (r) is circle radius, and (t) is the thickness of the slab.

II.9.1 Applications of Photonic Crystals:

Photonic crystals are fascinating optical materials that can be used to regulate and manipulate light flow. Thin-film optics based on one-dimensional photonic crystals are already widely used, with applications ranging from low and high reflection coatings on lenses and mirrors to color changing paints and inks. Higher-dimensional photonic crystals are attracting a lot of attention in both basic and practical research, and two-dimensional photonic crystals are starting to find industrial uses [65][66].

Photonic-crystal fibers, which use a micro scale structure to confine light with fundamentally different characteristics than ordinary optical fiber for applications in nonlinear devices and directing unusual wavelengths, are now available as the first commercial products involving two-dimensionally periodic photonic crystals. Photonic crystals are employed in other domains, such as bio-photonics, atomic physics, quantum computers, and communication appliances when some technical issues such as manufacturability and principal obstacles such as disorder are under control [67].

CHAPTER III

III.1 Introduction:

The fifth generation (5G) of cellular communication technology is now in an enhancement; with the challenge of meeting the high speed, power efficiency, and system dependability needs that come with more users, devices, and ambitious undertakings like Smart Cities and Autonomous Vehicles. . Antenna designs to improve the performance of 5G network, so an antenna array is designed and provided here to improve the microstrip patch antenna.

In this chapter, for the first step, we will start by studying the first antenna which is a microstrip patch array antenna. We will focus on the design based on a small size antenna at a 28GHz resonance frequency. Next, we will simulate to determine the parameters (return loss, bandwidth parameters, gain, directivity and radiation pattern...) using the CST Microwave Studio software. In order to increase the total gain of the antenna and have a wider bandwidth and take advantage of the functionality of the radiation overlay of several radiating elements in the same direction, we suggest the second step, which is the most important in order to design a microstrip patch array with photonic crystals.

III.2 Description of the CST Simulation Software:

CST Cable Studio is an electromagnetic simulation tool that combines transmission line, circuit, and 3D full-wave simulation to allow for the rapid and accurate investigation of real-world cables in complex electromagnetic environments of electrically large systems. It enables the investigation of multi-scale problems that would otherwise be difficult to solve with full-wave solvers. Cables with dimensions down to the micrometer range built in towers, cars, or aircraft with overall system dimensions in meters are examples of typical multi-scale problems. This allows it to be used for a wide range of electromagnetic problems, including hyper frequencies and temporal and frequency analysis [68].

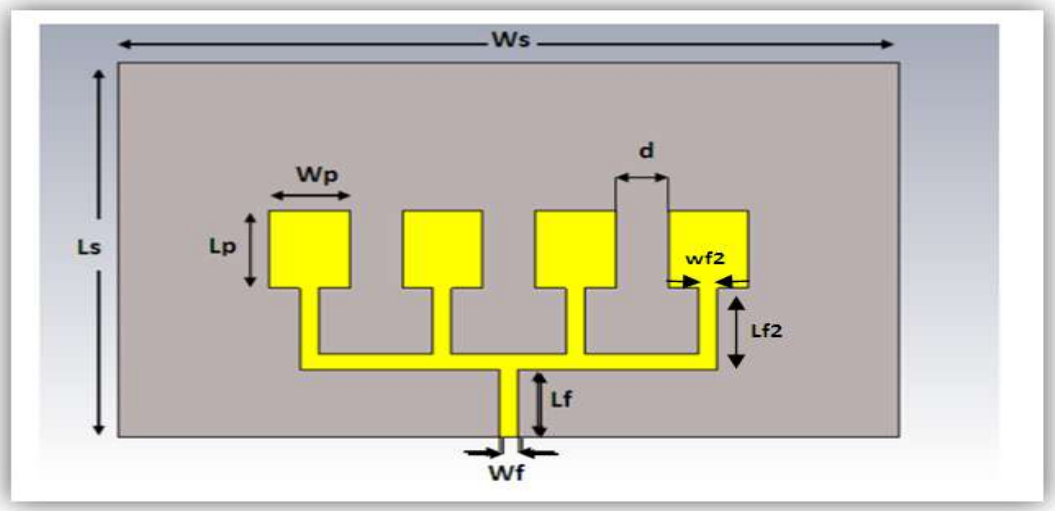
III.3 Design of microstrip patch array for the 28 GHz band

Antenna structure:

The antenna structure is proposed as shown FigureIII.1, Presents microstrip patch antenna that has a ground plane on the one side of a dielectric substrate which the side has a radiating patch, is generally made of conducting material such as copper or gold and can take

any possible shape. The dielectric constant of the substrate (ε_r) is typically in the range $2.2<\varepsilon_r<12$

We first choose the substrate, determine the resonant frequencies, and then calculate the antenna dimensions. This antenna is designed using FR-4(lossy) substrate and copper for the patch and ground. The dielectric constant of the used substrate is equal to 4.3 and its thickness is equal to 1.6 mm.



FigureIII.1 : 4 x 1 antenna array structure.

The dimensions of the antenna to be simulated are indicated in Table 2

Table2: Parameters of 4 x 1 Antenna array.

Parameters	Description	Value (mm)
Ws	Width of substrate	39
Ls	Length of substrate	24
Hg	Thickness of ground	0.0175
Hs	Thickness of substrate	1.6
Wp	Width of patch	3.990
Lp	Length of patch	5
Wf	Width of end feed	0.9435
Lf	Length of end feed	4.27822
D	Distance between patches	2.6457

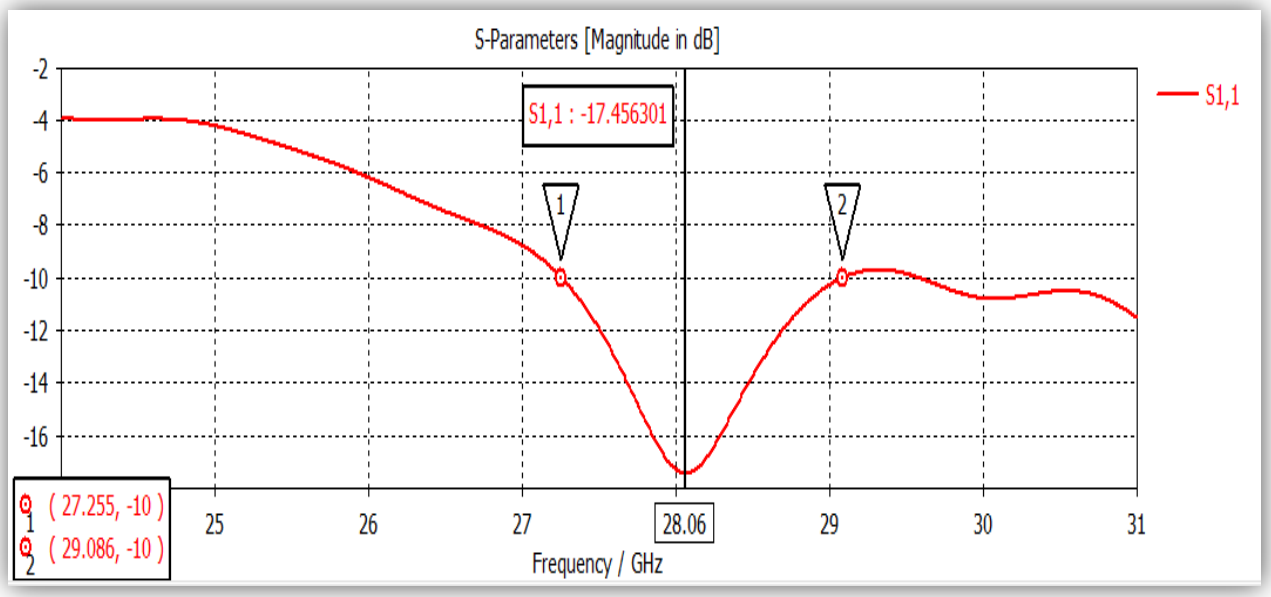
The patch is powered by a feed line with an input impedance of 75Ω.

III.4 Results and discussions:

Using the CST Microwave Studio Software, this antenna has been designed. The simulation results for return loss, radiation pattern, and VSWR.

III.4.1 Return loss:

The magnitude of the return loss parameter (S11) of the microstrip patch array exhibits adequate behavior, as shown in Figure III.2. The antenna resonates at 28 GHz, satisfying this design requirement.

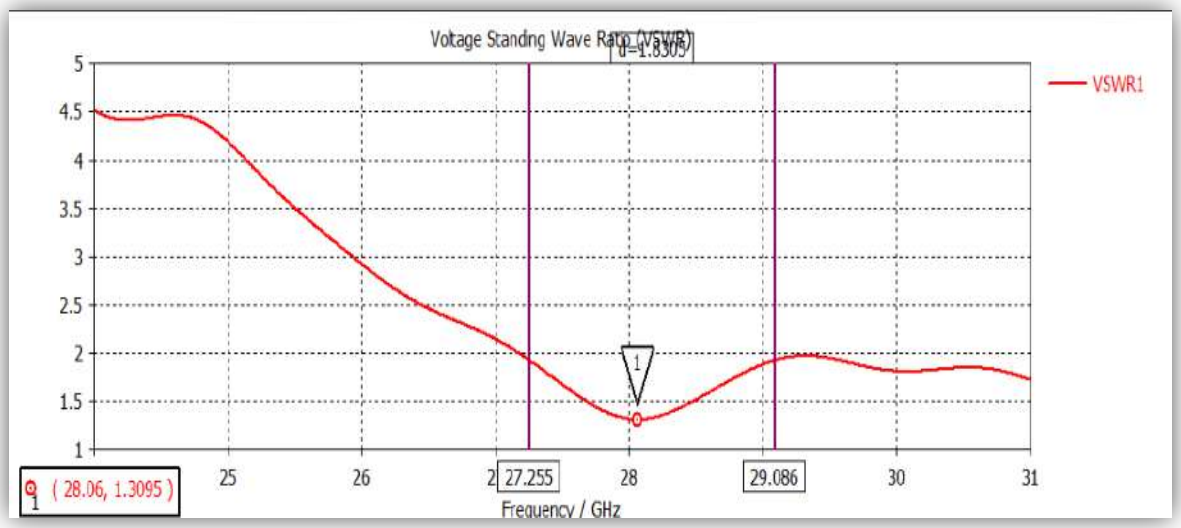


FigureIII.2: S11 in (dB) as a function of frequency.

It can be seen that the antenna has a maximum bandwidth of 1.831 GHz around the resonance frequency (28.06 GHz) in the range (27.255 - 29.086) GHz.

III.4.2 Voltage Standing Wave Ratio (VSWR):

The antenna's VSWR graph is shown in FigureIII.3. For the most part, the permissible VSWR for wireless applications should not exceed 2.5 and should ideally be 1.



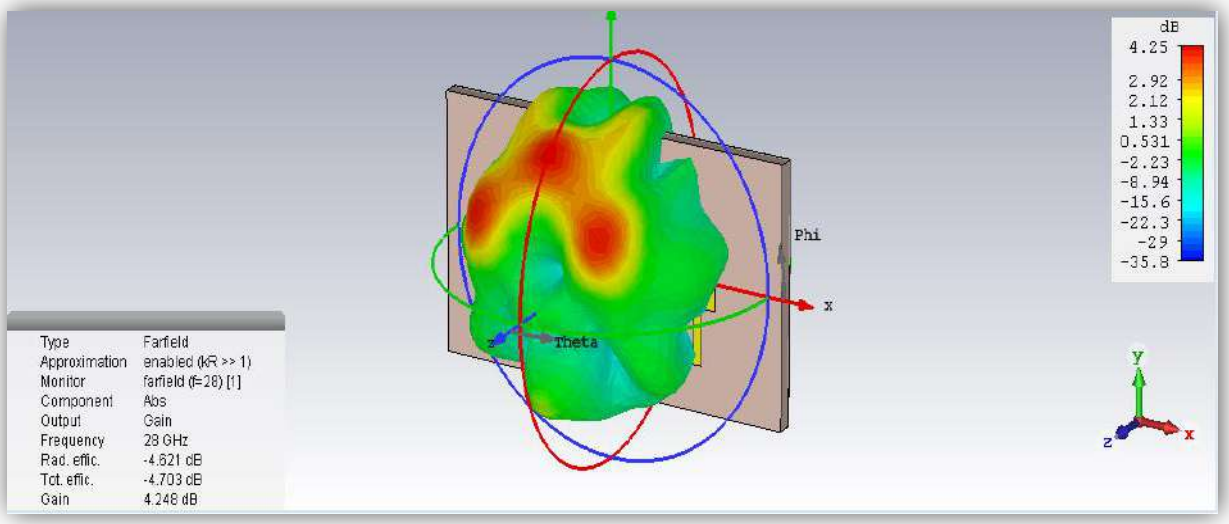
FigureIII.3 : Voltage standing wave Ratio as a function of frequency.

Like return loss S11, the Voltage Standing Wave Ratio also gives us the appreciation of adaptation. For the 28.06 GHz frequency, we found a VSWR equal to 1.3095 less than two in the bandwidth. This confirms that our antenna is very close to the resonant frequency, which is satisfactory.

III.4.3 Radiation patterns:

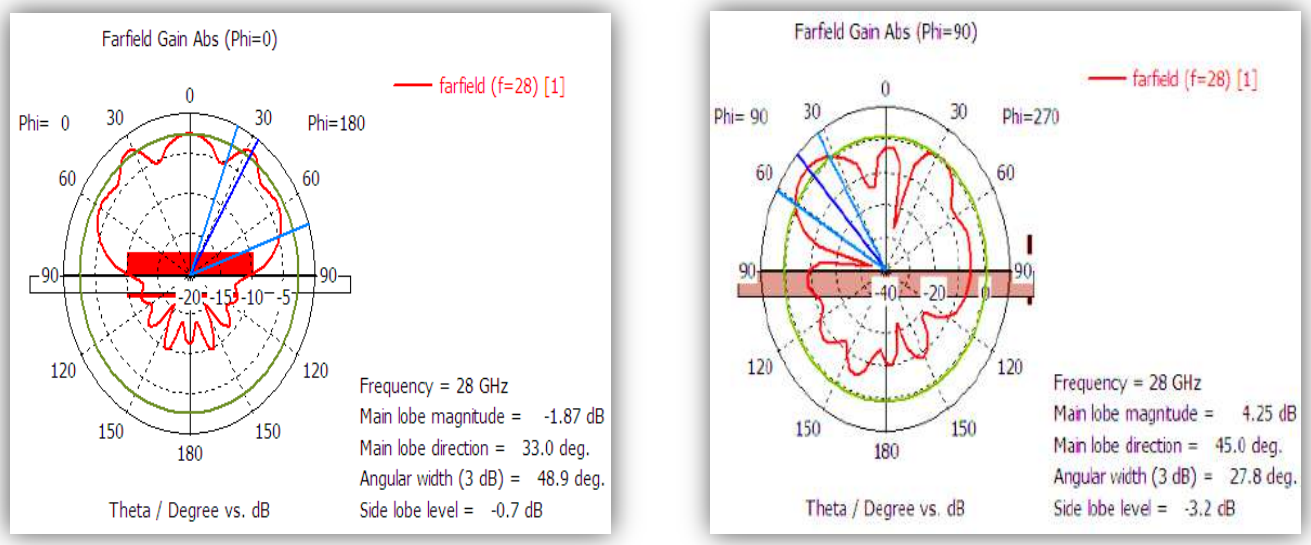
Using the previously mentioned design parameters, the model of the 3D radiation pattern is shown in the figures III.4:

III.4.3.1 Gain:



FigureIII.4 : Gain of 3D radiation pattern of 4 x 1 array antenna.

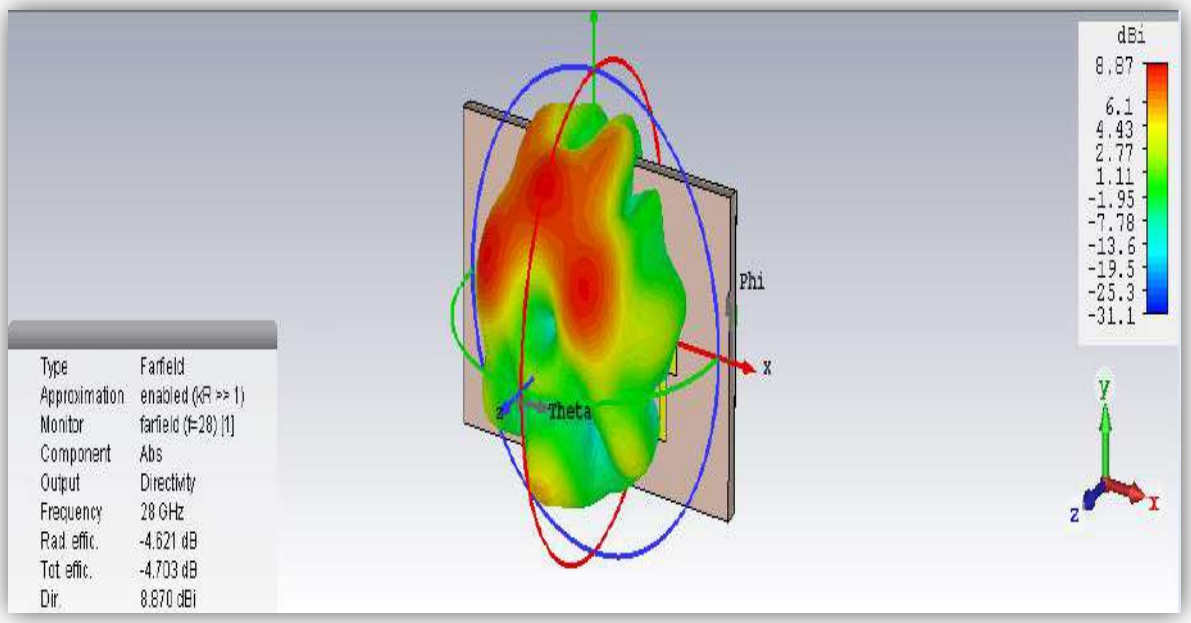
The form of the antenna radiation has an appropriate shape, as shown in Figures III.5 because the radiation is concentrated in the antenna's top plan.



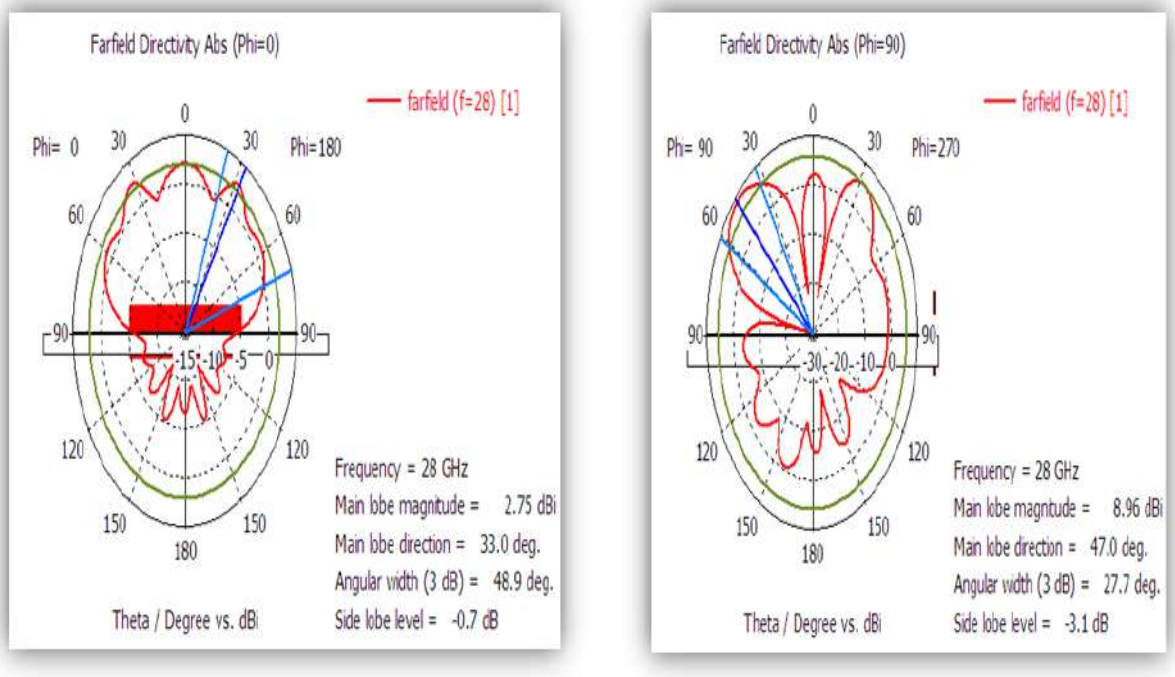
FigureIII.5 : 2D polar curve of the radiation diagram (gain) in (φ=0°) and (φ = 90°).

The bi-dimensional observation of this antenna's radiation pattern is used to visualize its components. The diagram is mainly composed of a main (major) lobe. This antenna is directive, and it has a gain of a maximum is 4.25dB.

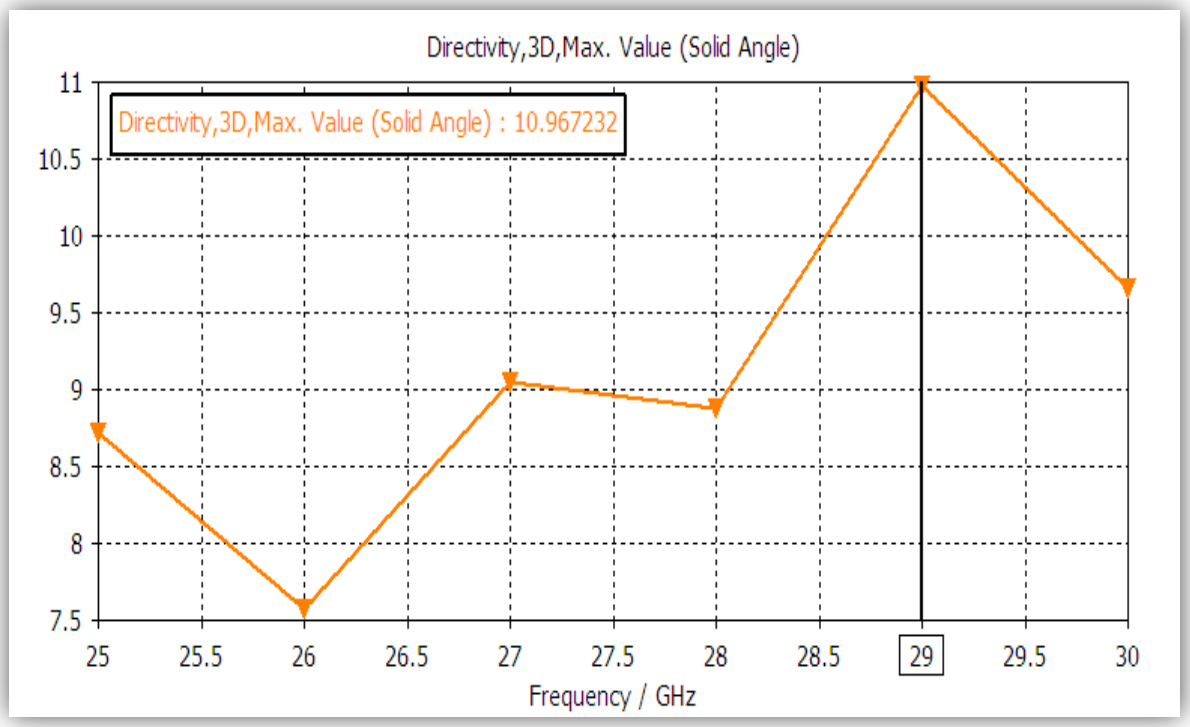
III.4.3.2 Directivity:



FigureIII.6 : Directivity of 3D radiation pattern of 4 x 1 array antennas.

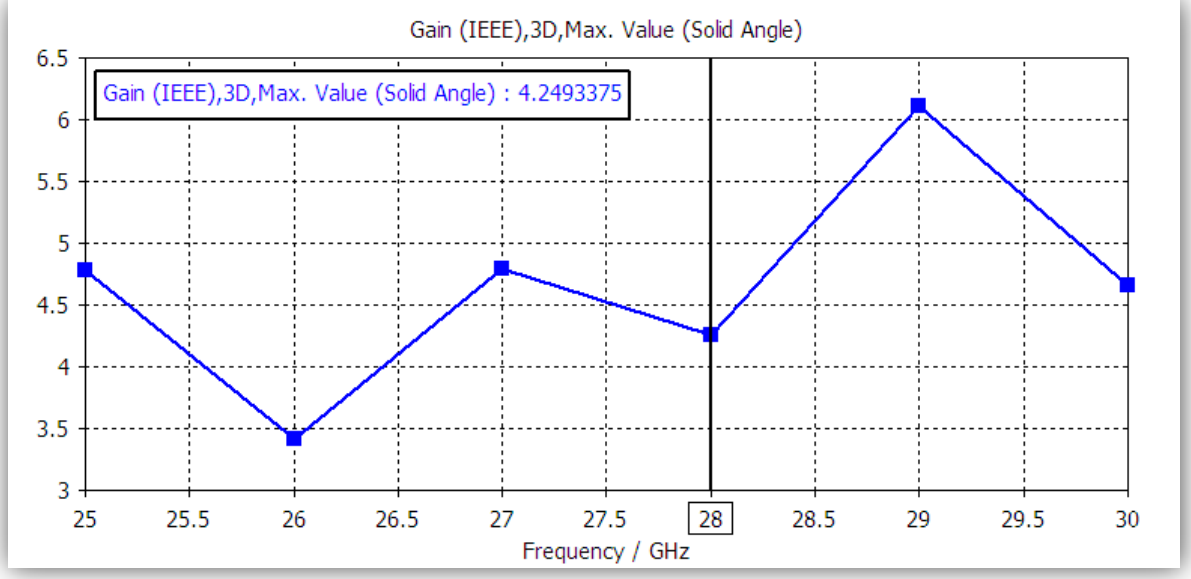


FigureIII.7 :2D polar curve of the radiation diagram of directivity in (φ=0°) and (φ = 90°).



FigureIII.8: Directivity as a function of frequency for antenna based on homogeneous substrate.

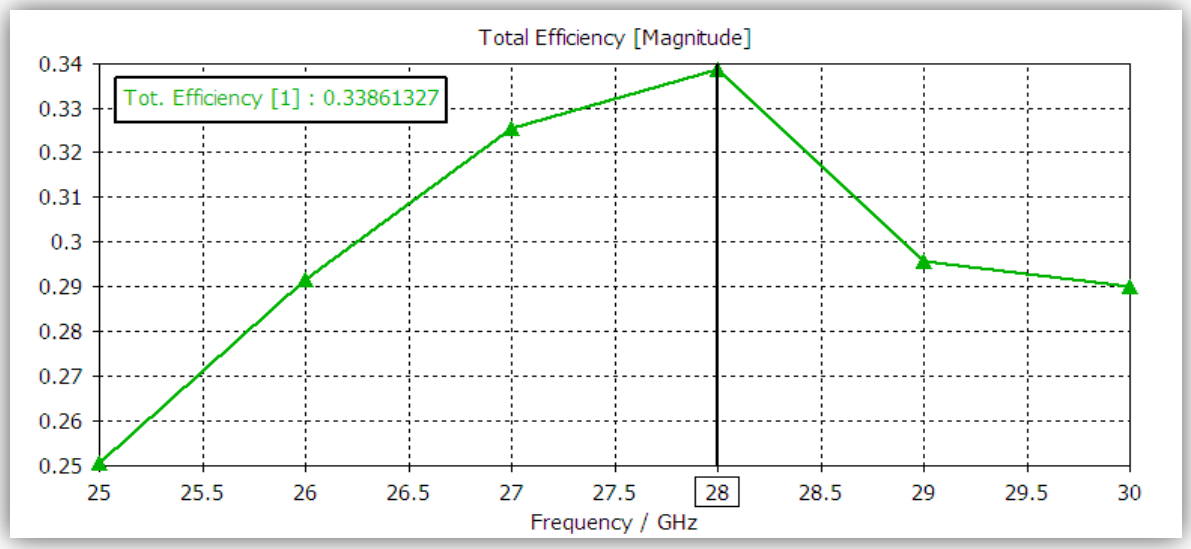
The max directivity value is 10.967dB in the frequency band of 29GHz.



FigureIII.9 : Gain as a function of frequency for antenna based on homogeneous substrate.

III.4.4 Efficiency:

The efficiency value of this antenna is 33.86% in frequency of 28 GHz.



FigureIII.10: The efficiency of an array antenna with photonic crystals.

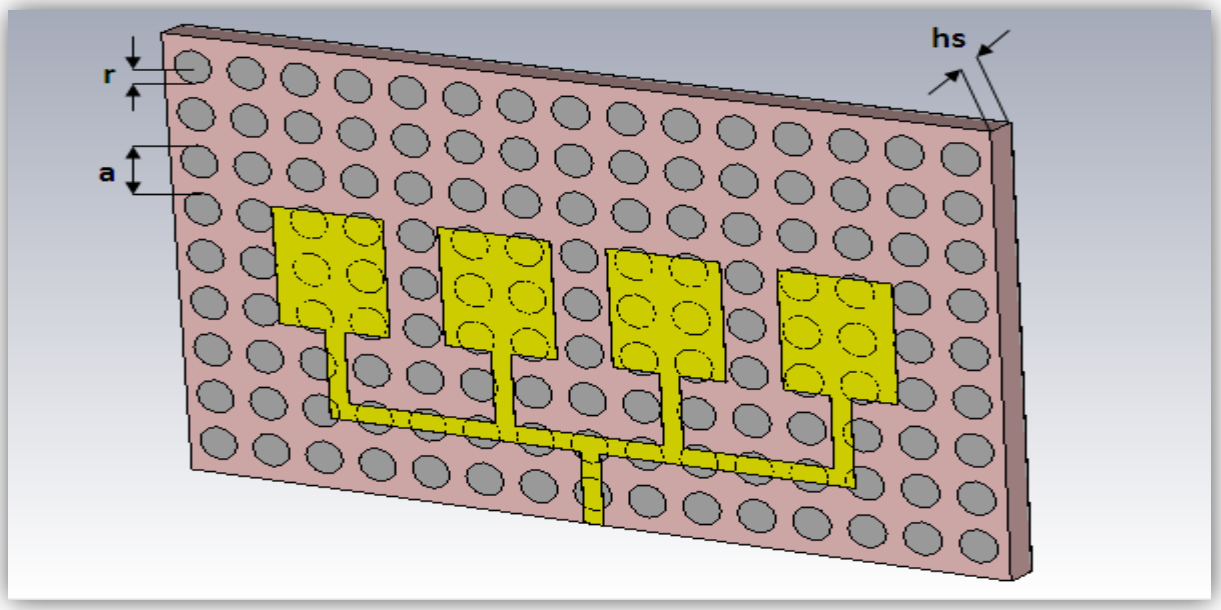
The value of the gain is 4.249 dB at the frequency is 28 GHz. The gain is currently insufficient to satisfy the 5G mobile requirements; we have to increase the antenna gain and bandwidth, also to narrows the angular width of the main lobe. As a result, it will be required to employ a microstrip patch array based on photonic crystals.

Table3: Result of 1 x 4 microstrip antenna array based on homogeneous substrate.

Parameters	Values
Return loss (dB)	17.456301
Band width (GHz)	1.831
VSWR	1.3095
Gain (dB)	4.25
Directivity (dB)	10.967
Efficiency (%)	33.86
Angular width	27.8 °

III.5 Design of antenna arrays with photonic crystals for the 28 GHz band from the previously designed element:

In this part, we added the previous antenna photonic crystals which featurethe air cylinders of a radius r=0.901059 mm and a period of 2.583mm are embedded in the host substrate. Hence, the dimension of the square unit cell is 2.583×2.583 mm^2 . A 4x1 microstrip patch antenna with photonic crystals is shown in the figure III.11:



FigureIII.11 : 4 x 1 antenna array with photonic crystals structure.

The table summarizes the values of the main parameters used in the design of our proposed antenna network.

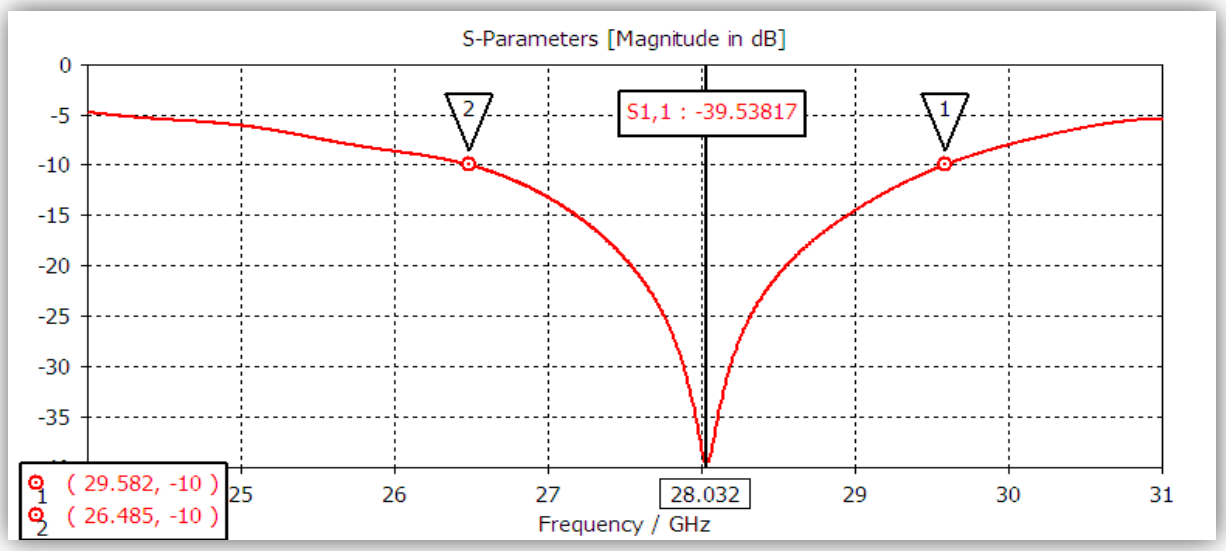
Table4: Parameters of 4 x 1 Antenna array with photonic crystals.

Parameter	Description	Value (mm)
Ws	Substrat width	39
Ls	Substrat length	24
Hs	Substrate thickness	1.6
Hg	Ground thickness	0.0175
Lp	Patch length	6.45
Wp	Patch width	5.35025
D	Distance between patches	2.6457
A	Lattice constant	2.583
R	Cylinder radius	0.901059

III.6 Results and discussions:

III.6.1 Return loss :

This graph shows S11 as a function of the frequency indicating the fundamental resonance frequency of 28.032 GHz .

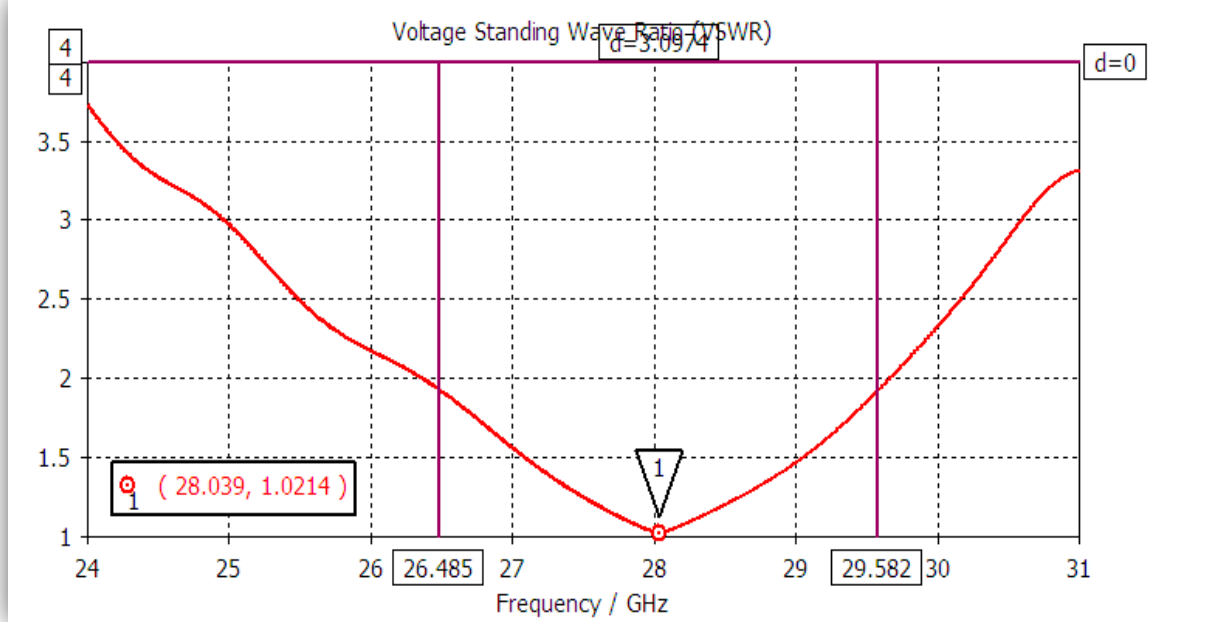


FigureIII.12 : Return loss (S11) in (dB) as a function of frequency.

It can be seen that the antenna has a maximum bandwidth of 3.097 GHz around the resonant frequency of 28.032 GHz in the range of (26.485 - 29.582) GHz .

III.6.2 Voltage Standing Wave Ratio VSWR:

The antenna standing wave ratio (VSWR) graph is shown in the figure III.13.The acceptable level of VSWR for most wireless applications should be in the range between 1 and 2, As shown in the figure, the VSWR value obtained at the resonance frequency of28.039 GHz is 1.0214.



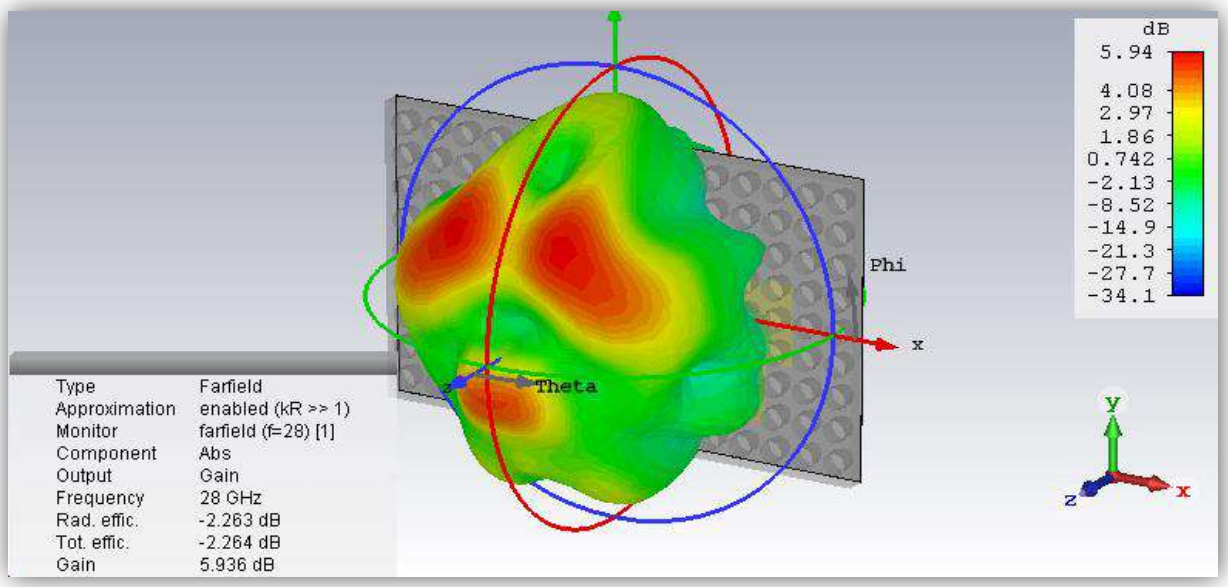
FigureIII.13: Voltage standing wave Ration as a function of frequency.

The obtained values of VSWR are less than 2 and very close to the ideal value of 1, which validated the condition for perfect impedance matching.

III.6.3 Radiation pattern:

III.6.3.1 Gain:

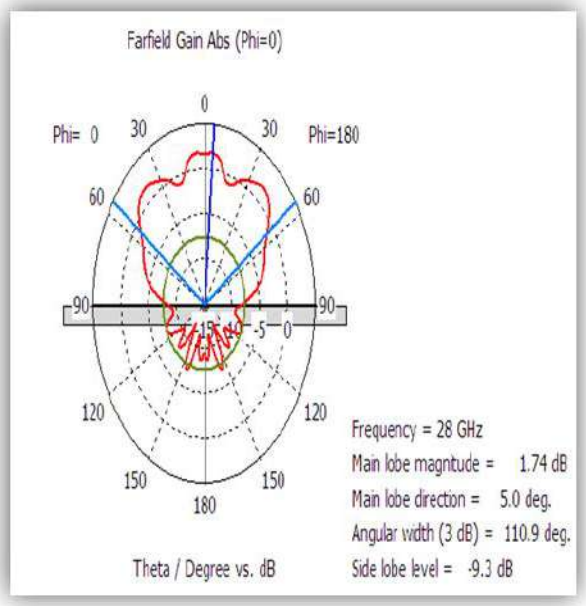
The gain and Directivity are essential characteristics for the antennas, using the above-mentioned design parameters; the diagram template 3D directivity of this antenna is predicted using the CST simulation software as shown in the figure III.14:

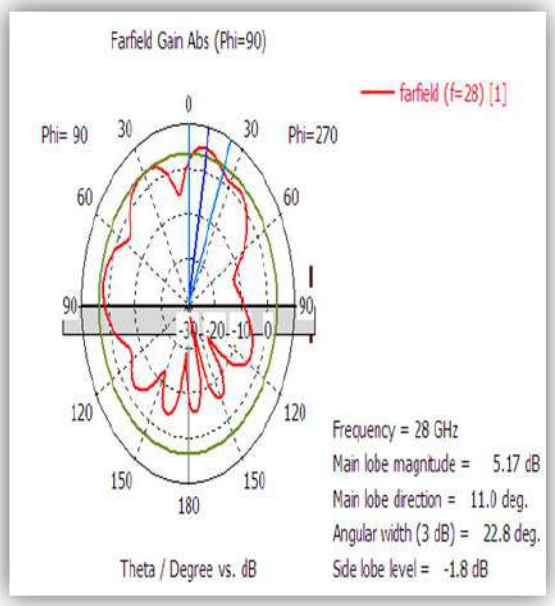


FigureIII.14 : Gain of 3D radiation pattern of 4 x 1 array antennas with photonic crystals.

The obtained results indicated that the gain was enhanced for the antenna array that is designed based on periodic PBG substrate with values of 5.94 dB.

The radiation pattern of array antenna has an appropriate shape, such as shown in the figure III.14 since the radiation is concentrated in the upper plane of the antenna, as it is normally the case with this type of network.

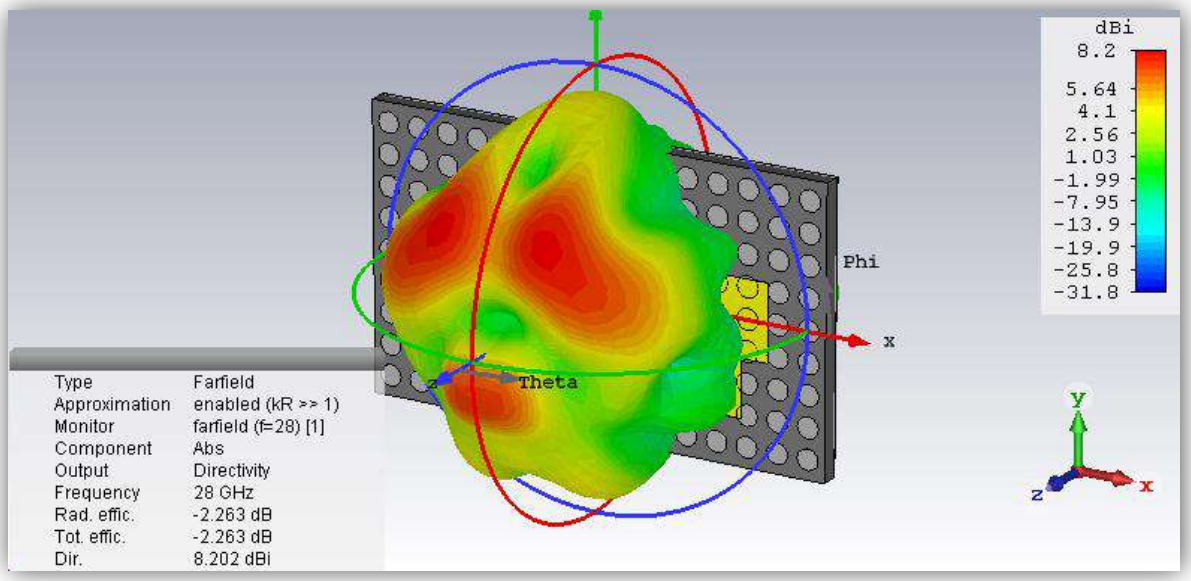




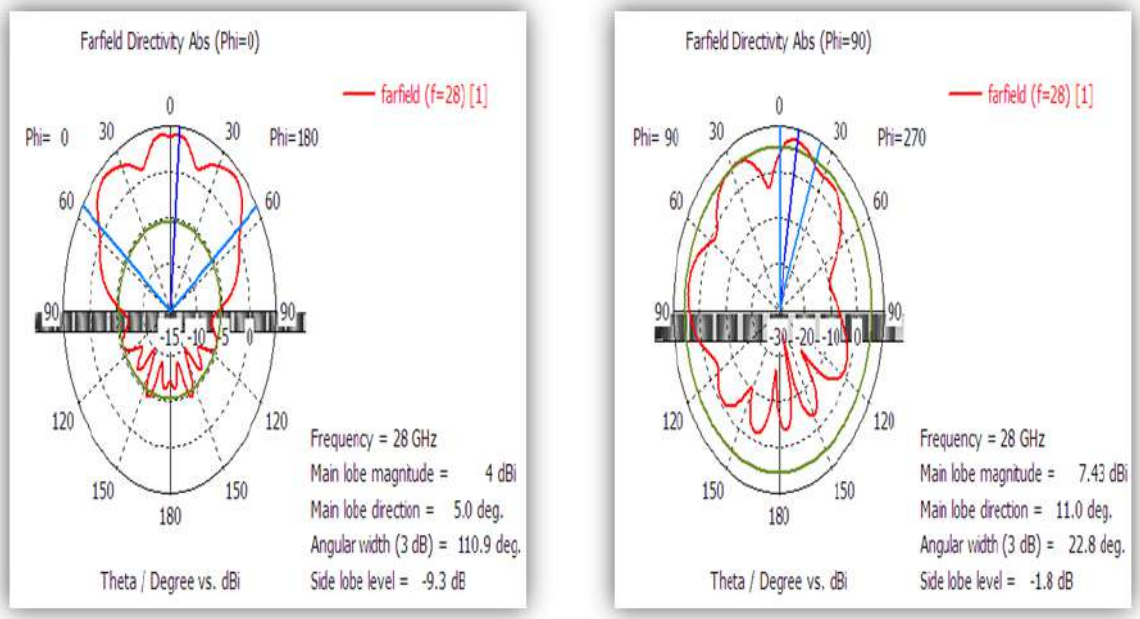
FigureIII.15 :2D polar curve of the radiation diagram (Gain) in (φ=0°) and (φ = 90°)

In this part, our antenna is more directive compared to the first part with value of the main lobe magnitude is 5.17dB.

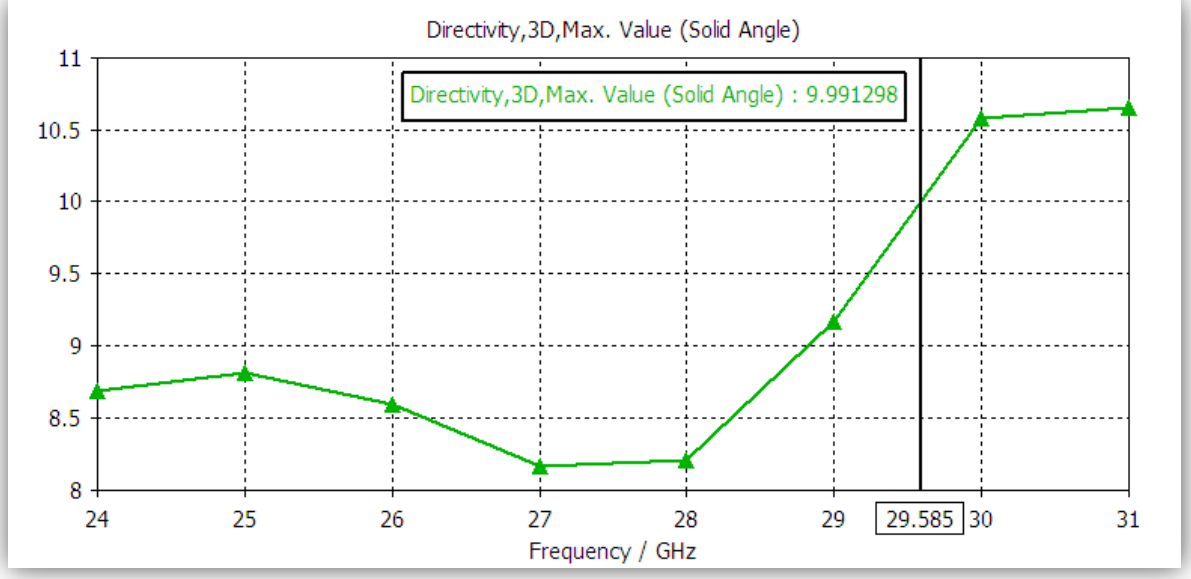
III.6.3.2 Directivity:



FigureIII.16 : Directivity of 3D radiation pattern of 4 x 1 array antennas with photonic crystals.

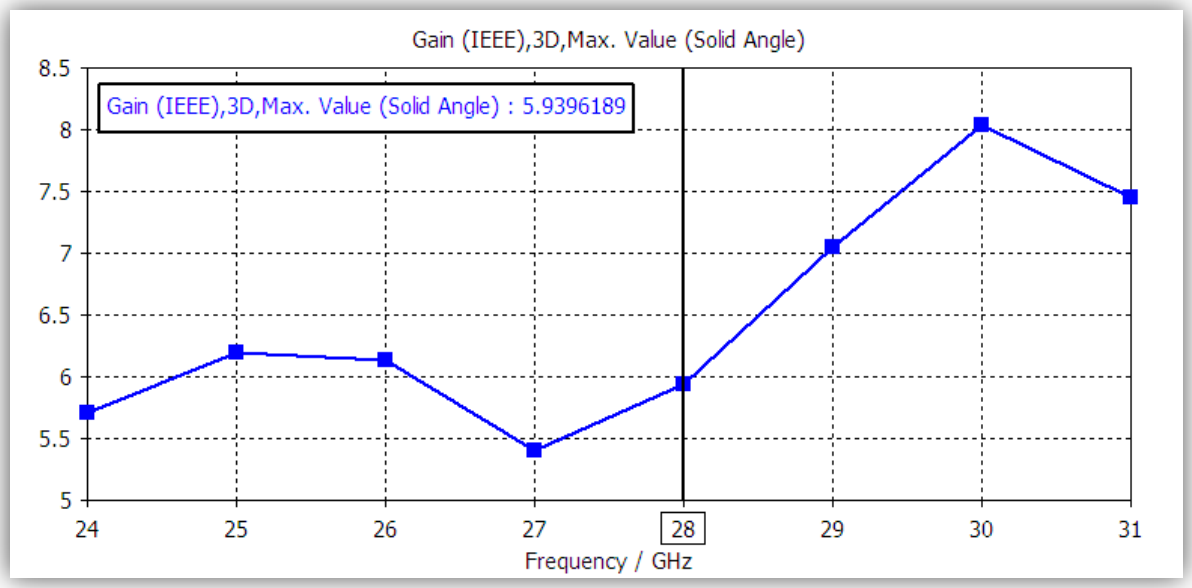


FigureIII.17 :2D polar curve of the radiation diagram of directivity in (φ=0°) and (φ = 90°).



FigureIII.18: Directivity as a function of frequency based on PBG substrate.

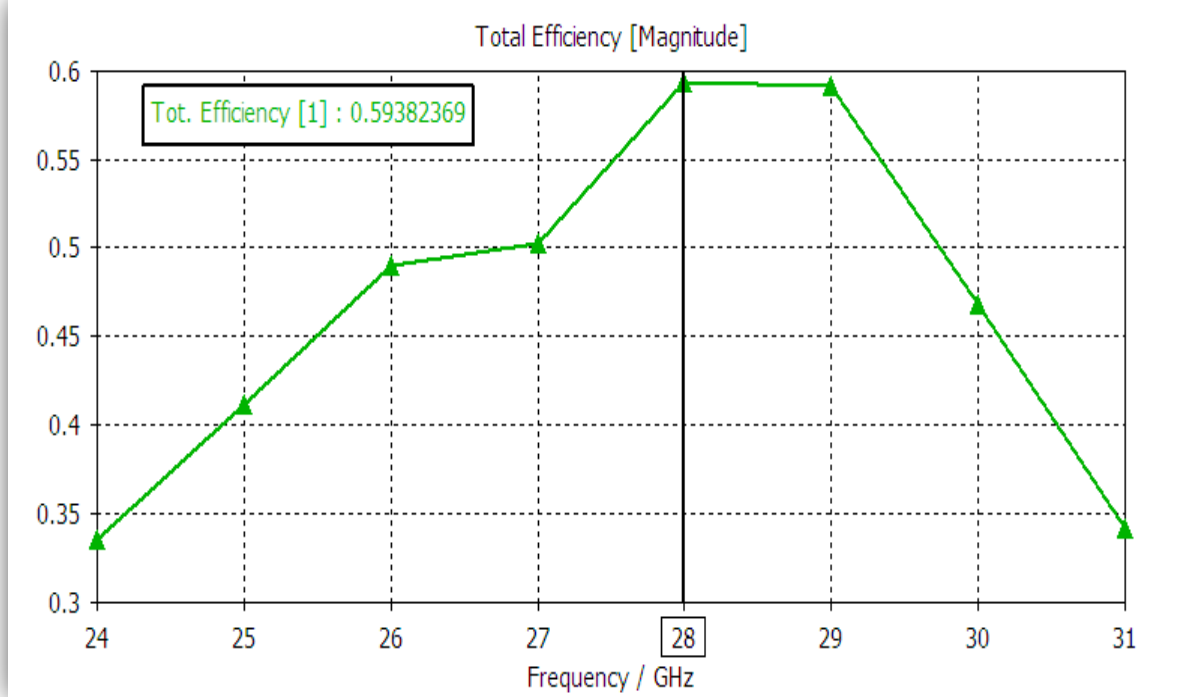
The max directivity value is 9.991 dB in the frequency band of 29.585GHz.



FigureIII.19 : Gain as a function of frequency based on PBG substrate.

III.6.4 Efficiency:

The efficiency value of this antenna is 59.39% in frequency of 28 GHz.



FigureIII.20: The efficiency of an array antenna with photonic crystals.

The previously examined parameters of the proposed antenna array for the 28 GHz band are summarized in Table 5.

Table5: Result of 1 x 4 microstrip antenna array on PBG substrate.

Parameters	**Values**
Return loss(dB)	39.53817
VSWR	1.0214
Bandwidth (GHz)	3.0974
Gain (dB)	5.94
Directivity (dB)	9.991
Efficiency (%)	59.38%
Angular width	22.8 °

III.7 Comparison between homogeneous and periodic PBG antenna:

During the last few years, significant efforts have been made to develop antenna networks for the 5G application. To validate the performance of our antenna we compare our antenna with and without photonic crystals. The following table summarizes the points of comparison.

Table 6: Comparison between two antennas.

Parameters	Homogeneous substrate	periodic PBG substrate
Return loss S11 (dB)	17.456301	39.53817
Resonance frequency (GHz)	28.06	28.039
VSWR	1.3095349	1.0214
Gain (dB)	4.25	5.94
Efficiency(%)	33.86	59.38
Bandwidth (GHz)	1.831	3.0974

When we compare the results, we notice that PBG substrate has improved our antenna. We got good results compared to a homogeneous substrate and get closer to the requirements of the 5G mobile.

Conclusion:

In this chapter, we designed and simulated 1 x 4 microstrip patch antenna array around28 GHz, first the proposed antenna array was designed based on the homogeneous substrate. To improve the return loss, bandwidth, gain, and radiation efficiency we add photonic crystals in the substrate for suppressing undesirable surface waves and obtaining better results.

GENERAL CONCLUSION

Mobile communications are becoming progressively demanding as far as transport a huge amount of data with more speed and capacity to support massive machine-to-machine communications, reliably connect an extremely large number of devices and process very high volumes of data with low-latency. To this end, the fifth generation (5G) of mobile technologies has increased the speed of data transfer and improved bandwidth over existing fourth generation (4G) technologies. It connects people, things, smart homes and buildings and cities, data, transport systems, work and play in the cloud and remote medical services. To meet the dramatic traffic growth, diverse reconfigurable antenna types have been designed, fabricated and properly characterized from microwaves to mm-waves, with the aim of fulfilling the requirements of 5G networks.

The main goal of this dissertation is to investigate and design a multi-service millimeter antenna using CST simulation program for 5Gnetwork and to create a microstrip patch array antenna system for a 5G application in the millimeter-wave band. It addresses the following issue: how can advanced transmission techniques improve transmission performance in mobile wireless networks? How to remove surface waves?

We started our investigation by focusing on the antenna design. Clearly, the antenna must provide better performance in the desired band, which is around the frequency of 28 GHz. Also, to improve the results by suppressing undesirable surface waves. Our preference has shifted to a microstrip patch array based on a photonic crystals antenna which enhances the characteristics of the conventional 1 × 4 microstrip patch antenna array.

The obtained results represent a better compromise in terms of size, gain, and bandwidth. The proposed antenna has the advantages of a large bandwidth and an appropriate gain. These results make this antenna a viable candidate for future wireless communication components and other millimeter-wave applications. An efficient antenna at 28GHz for 5G communications applications has been successfully designed. First of all, a parametric study of different parameters that affect antenna performance, (such as antenna type, feeding technique, substrate dielectric constant, substrate thickness, substrate loss tangent, etc.…) was performed using CST simulation software. According to this study, the best substrate material in terms of efficiency and bandwidth is FR-4(lossy) with dielectric constant ϵ_r= 4.3 and thickness(h)=1.6mm.

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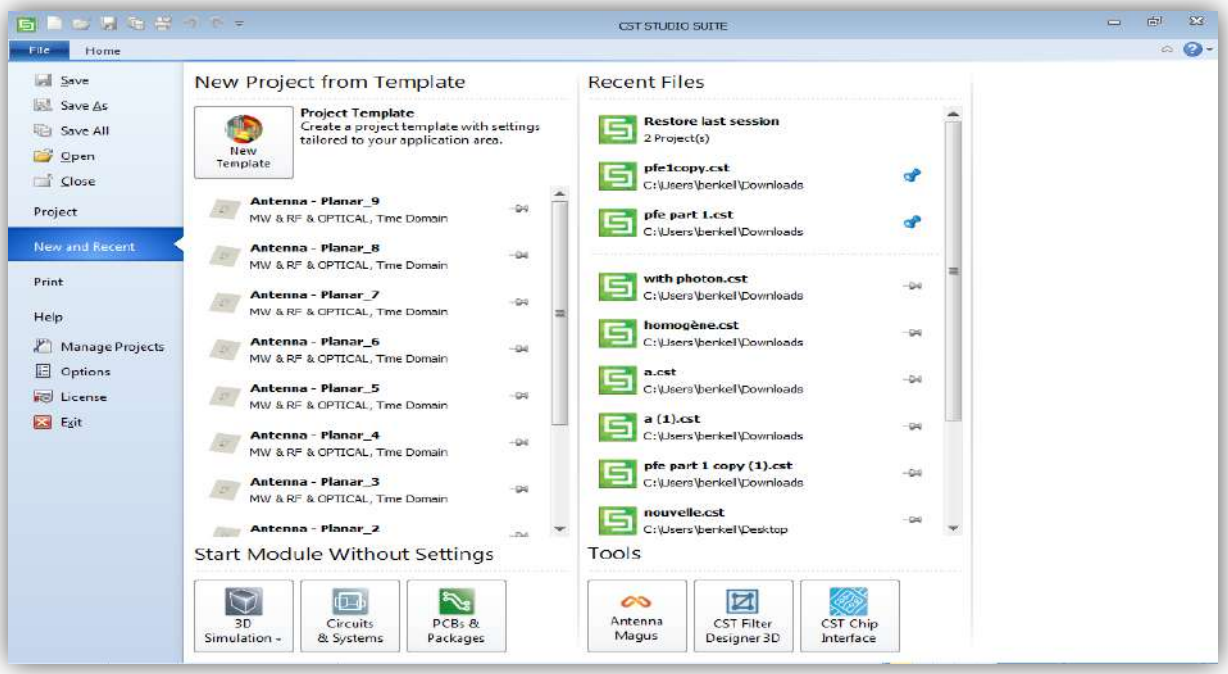
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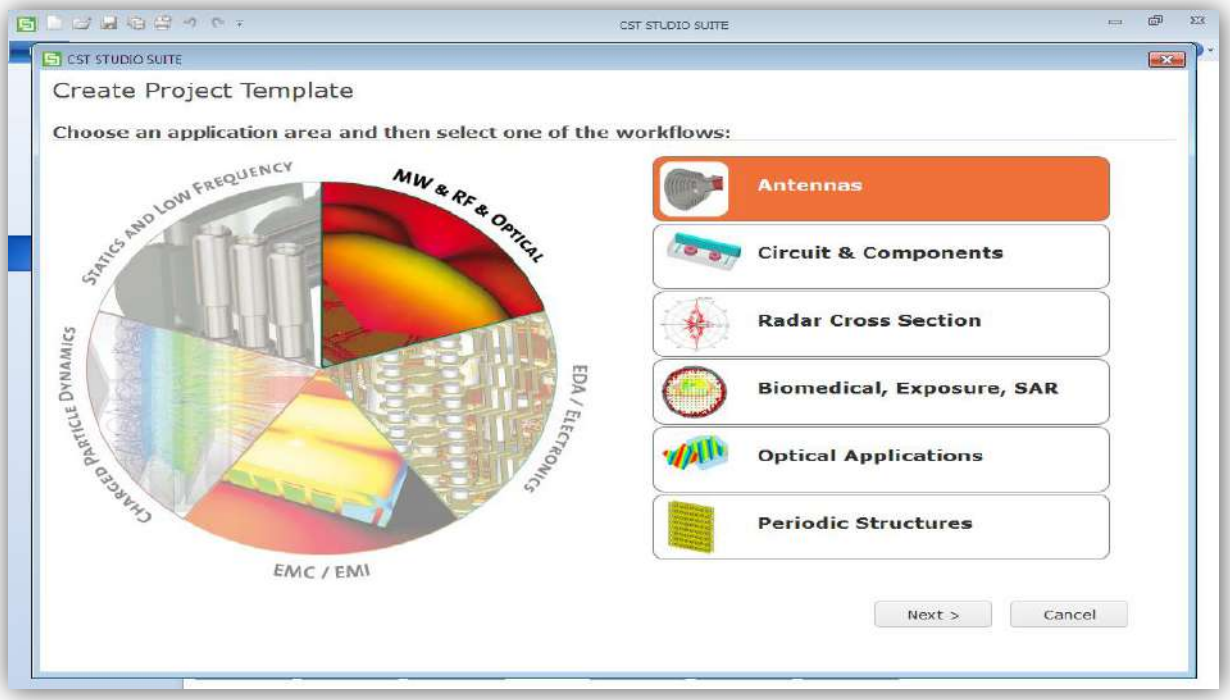
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ANNEX

1) CST Studio Main Window Launch

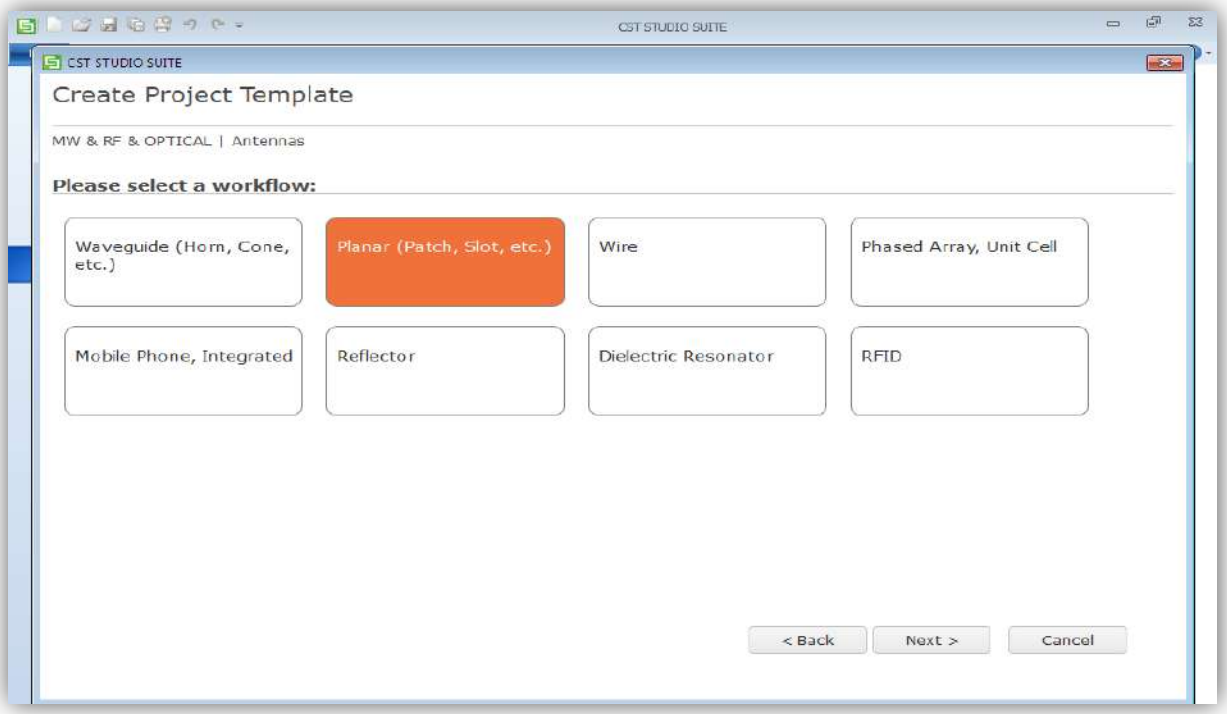


2) Selection of the field of application in CST:

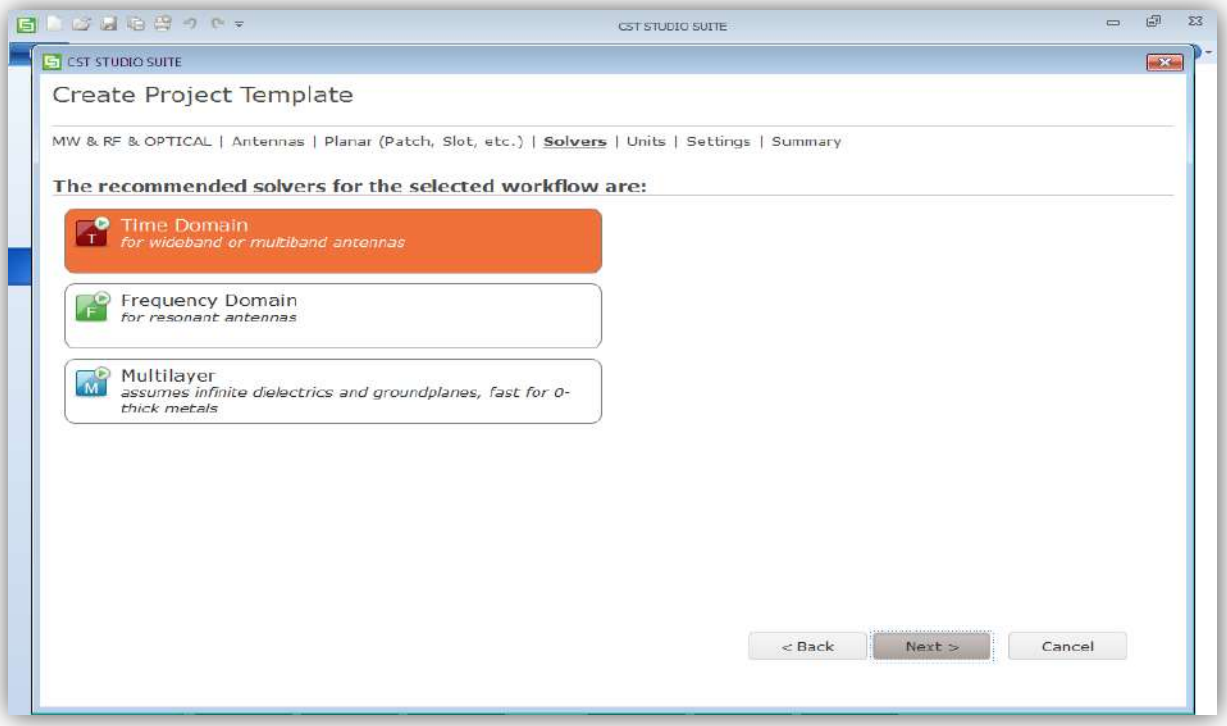


The above window requires selection of an application area and specification type of work to be performed, in this case selecting the MW & RF & Optical field, in particular Antennas.

3) Choice of antenna type to be implemented in CST:

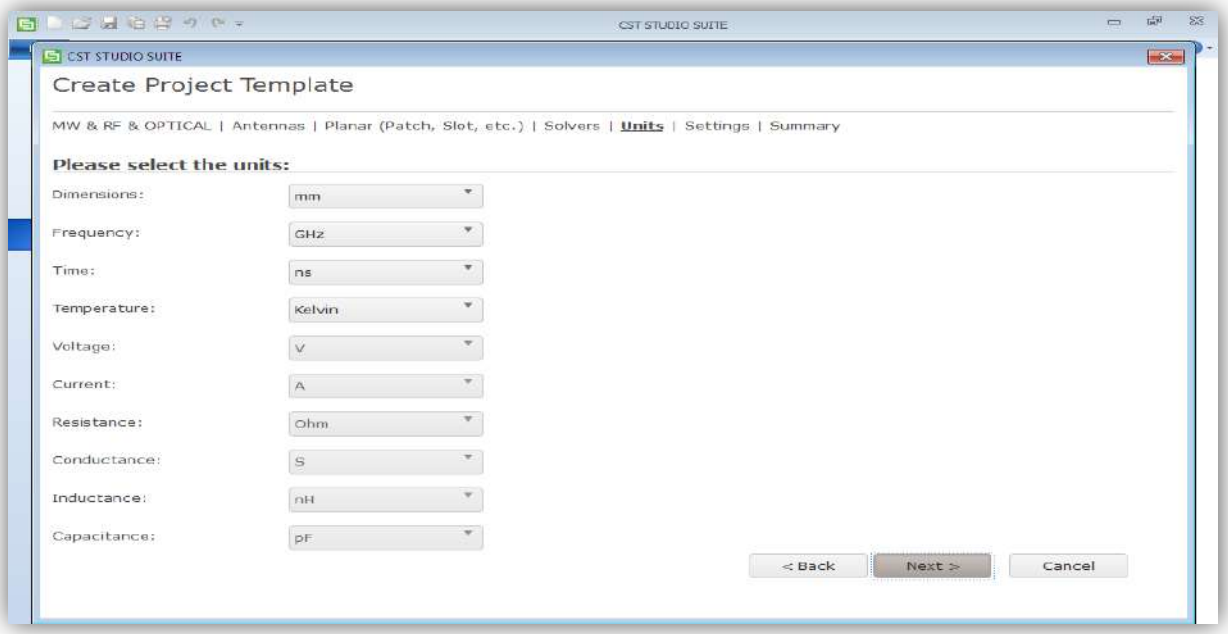


4) Selection of the type of simulation to be used in CST:

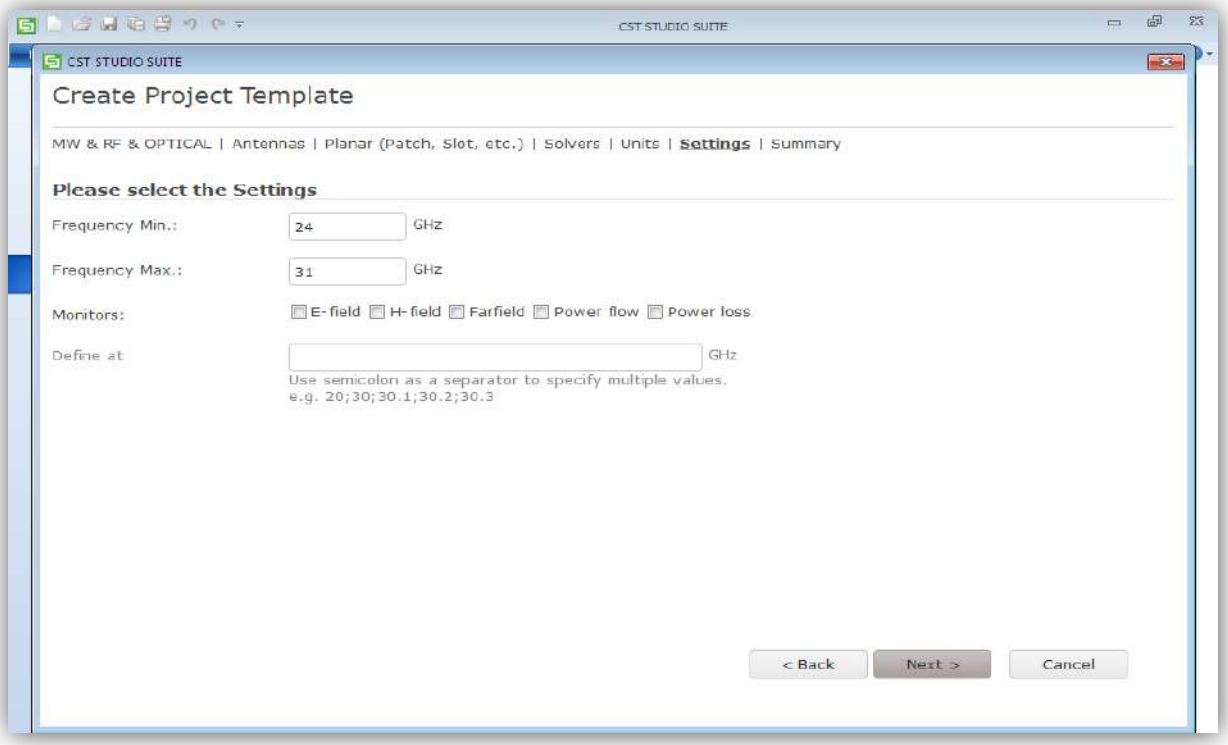


The field time mode has been chosen. In the time domain, the transient solver can solve most electromagnetic field problems and analyze an antenna with good accuracy

5) Selection of units of measure to be used in CST:

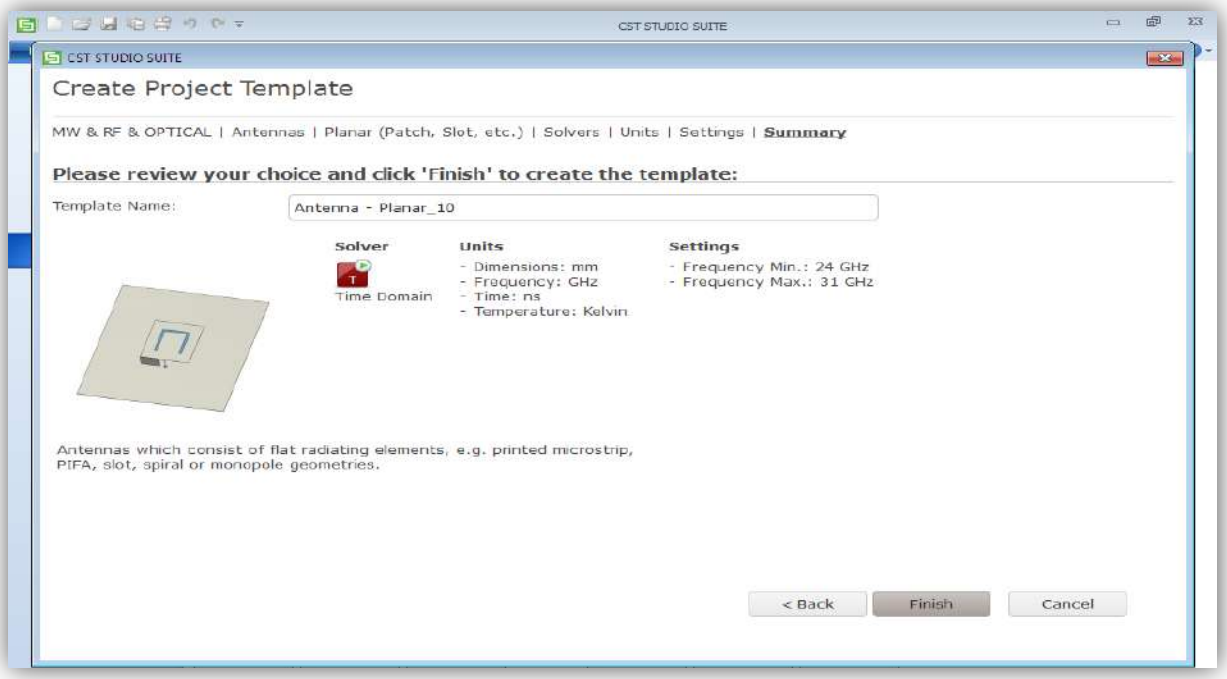


6) Configuring the frequency range and monitors to be analyzed:

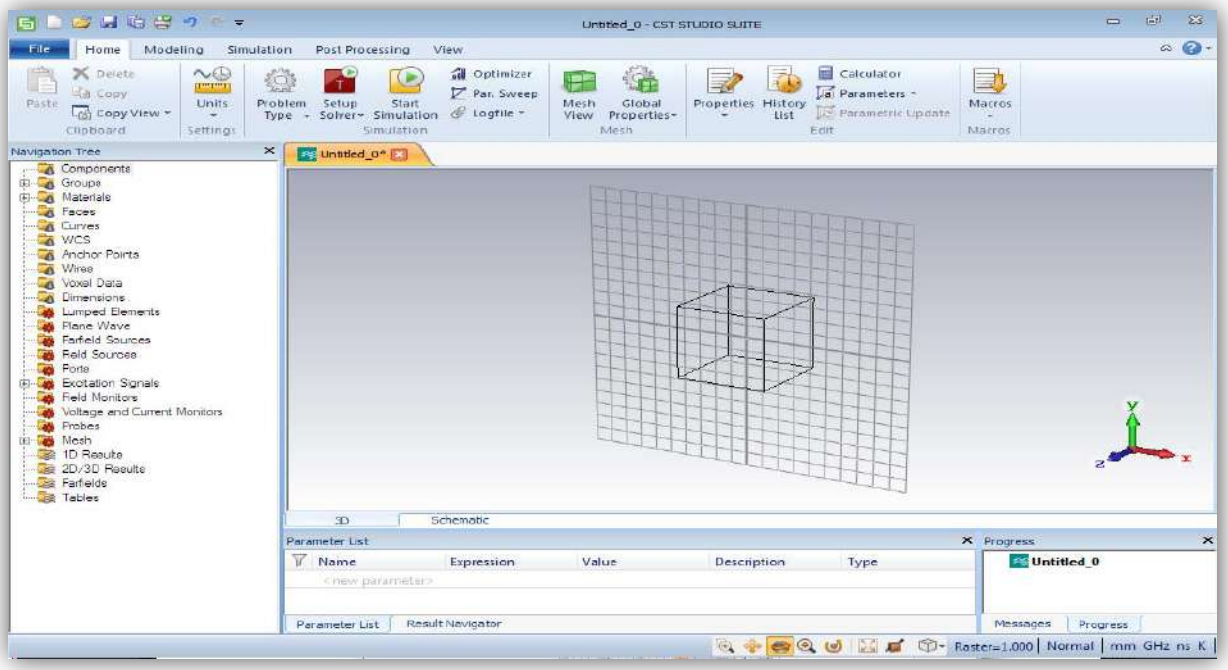


In this step, we define the frequencies of interest and what should be monitored, in this case the frequencies between 24 and 31 GHz, with 28 GHz being the central frequency.

7) Name and summary of template configurations created in CST:

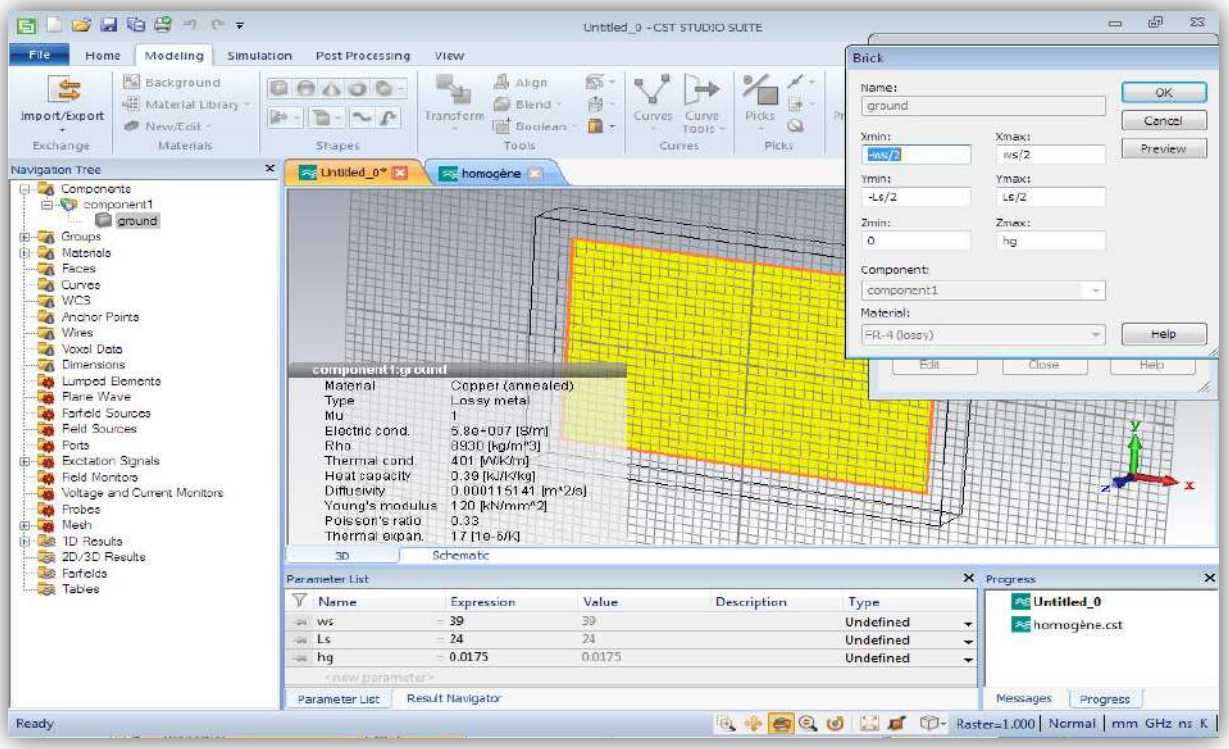


8) CST Microwave Studio Workspace:

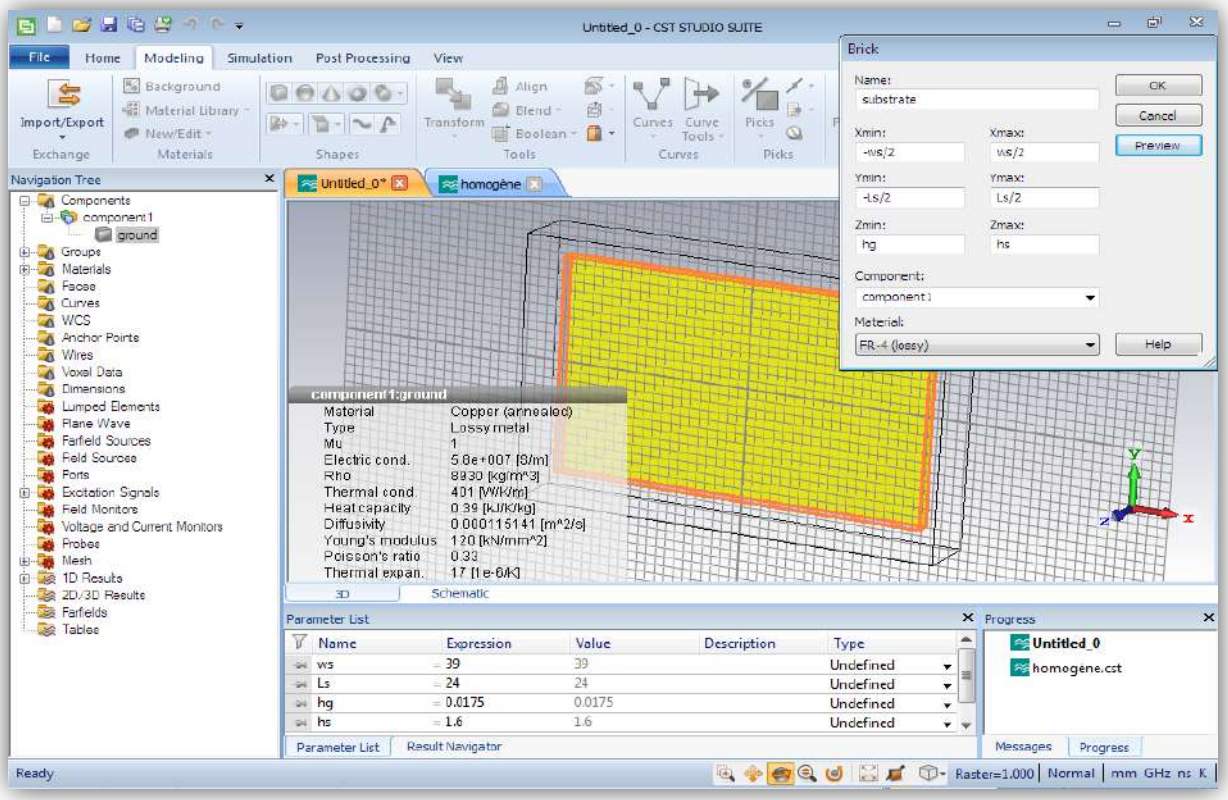


In this phase, a project model is created in CST Microwave Studio, appearing in a window that constitutes the workspace in which the modeling of the patch antenna must be performed.

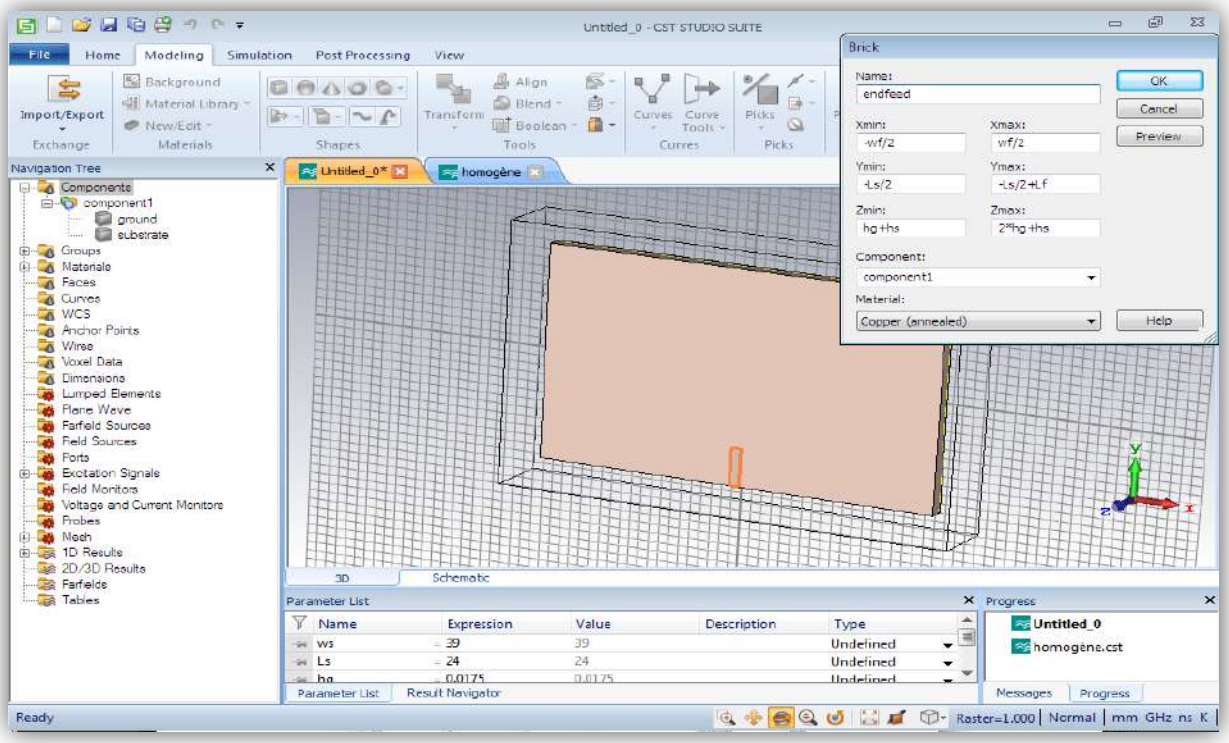
9) Microstrip Ground Plane Modeling:



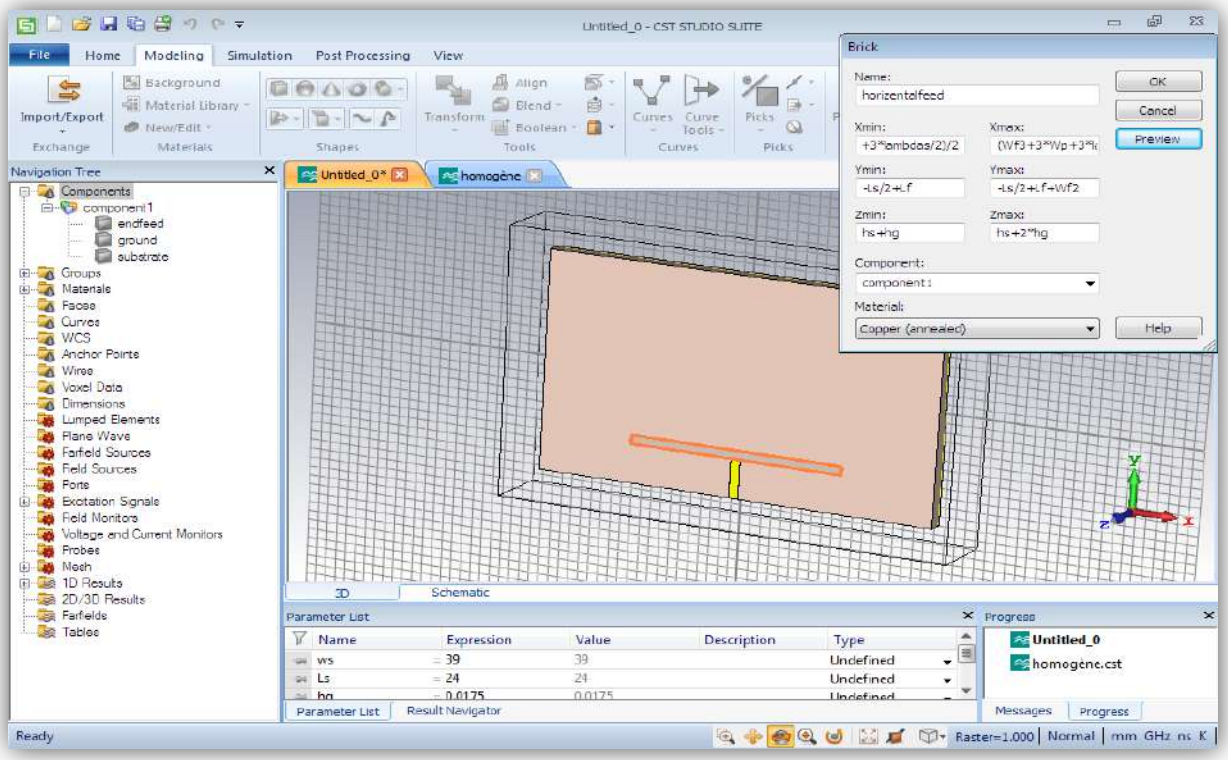
10) Microstrip substrate Plane Modeling:



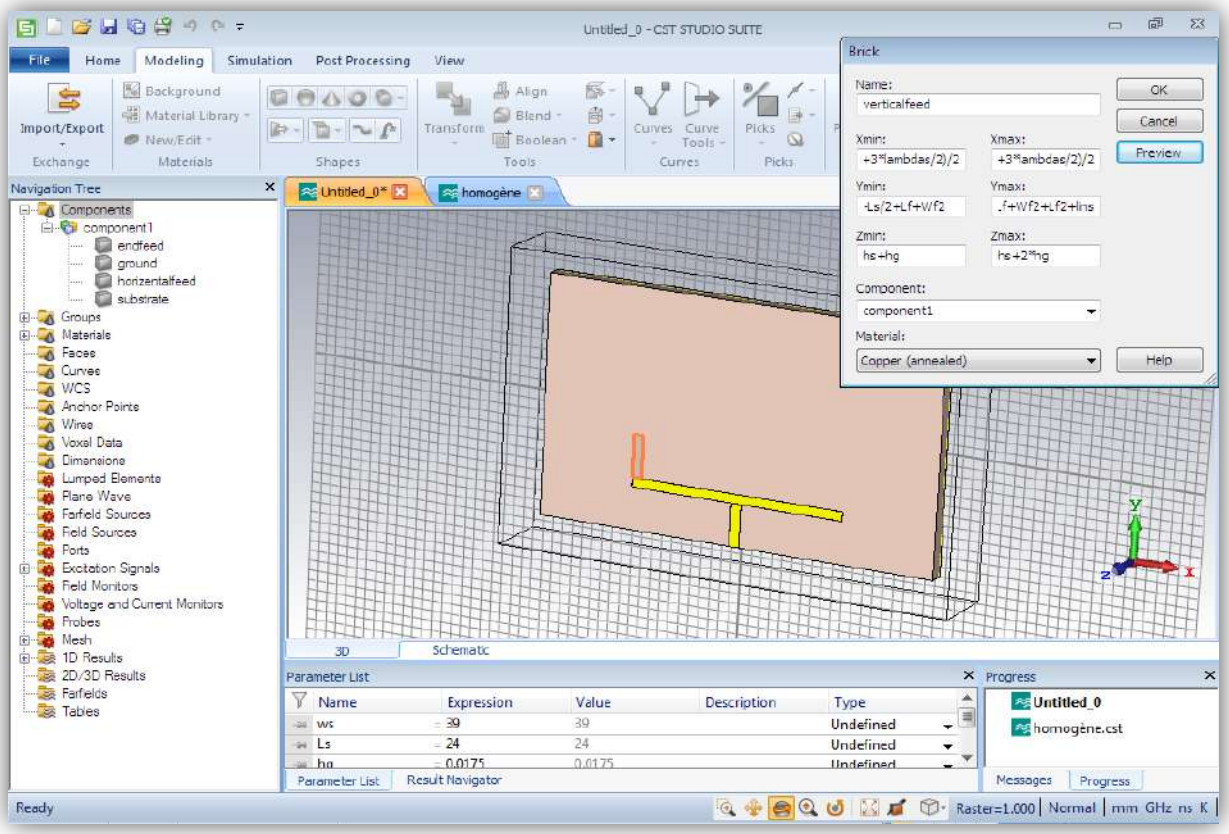
11) Modeling end feed:

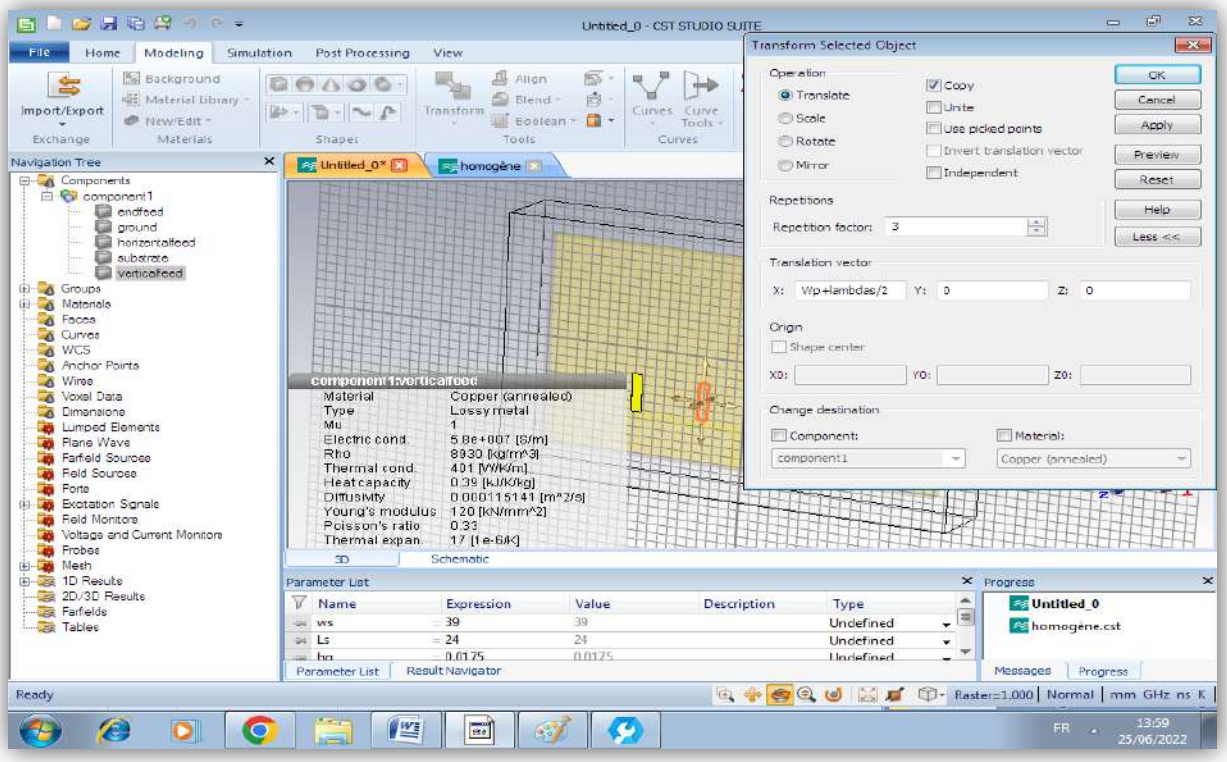


12) Modeling Horizontal feed:

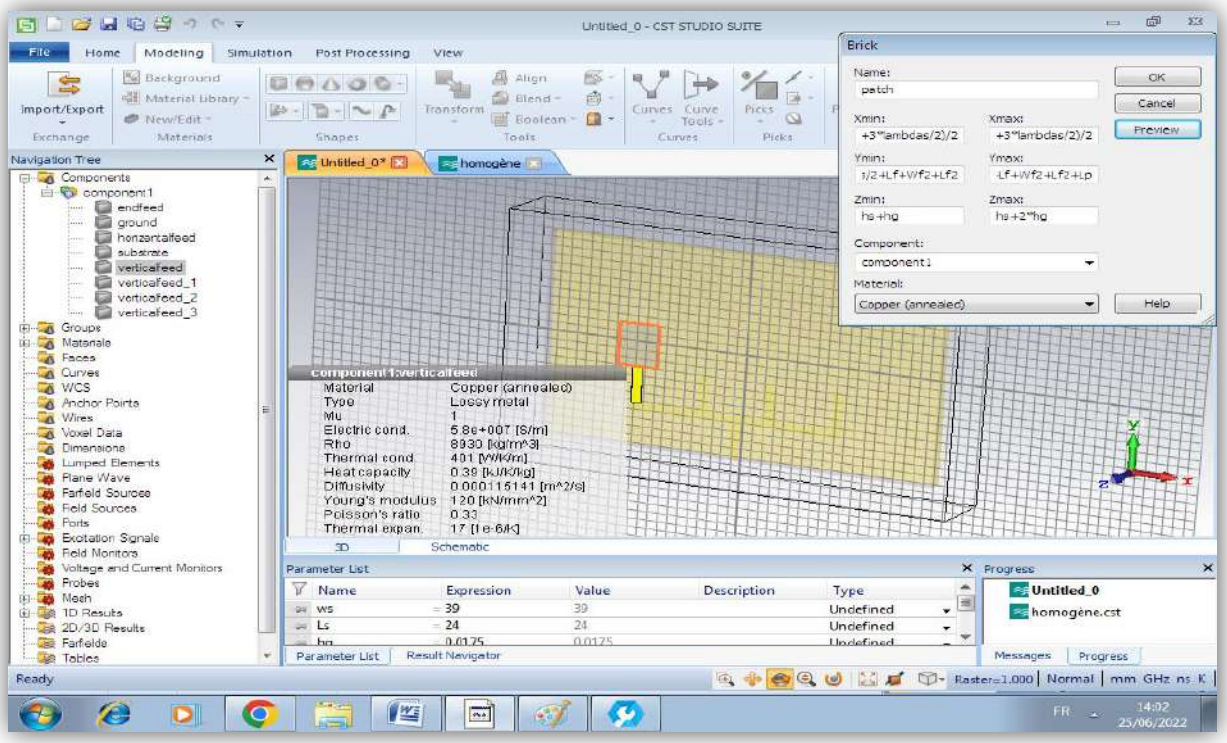


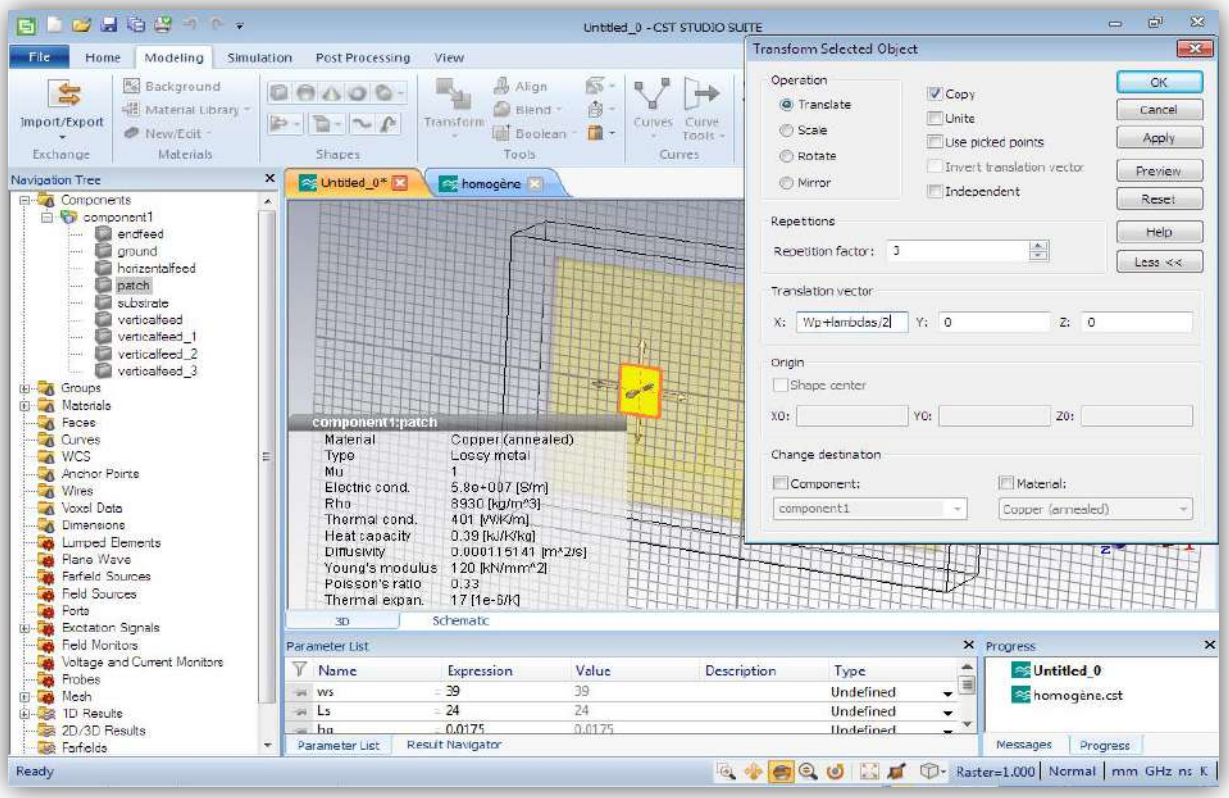
13) Modeling Vertical feed:

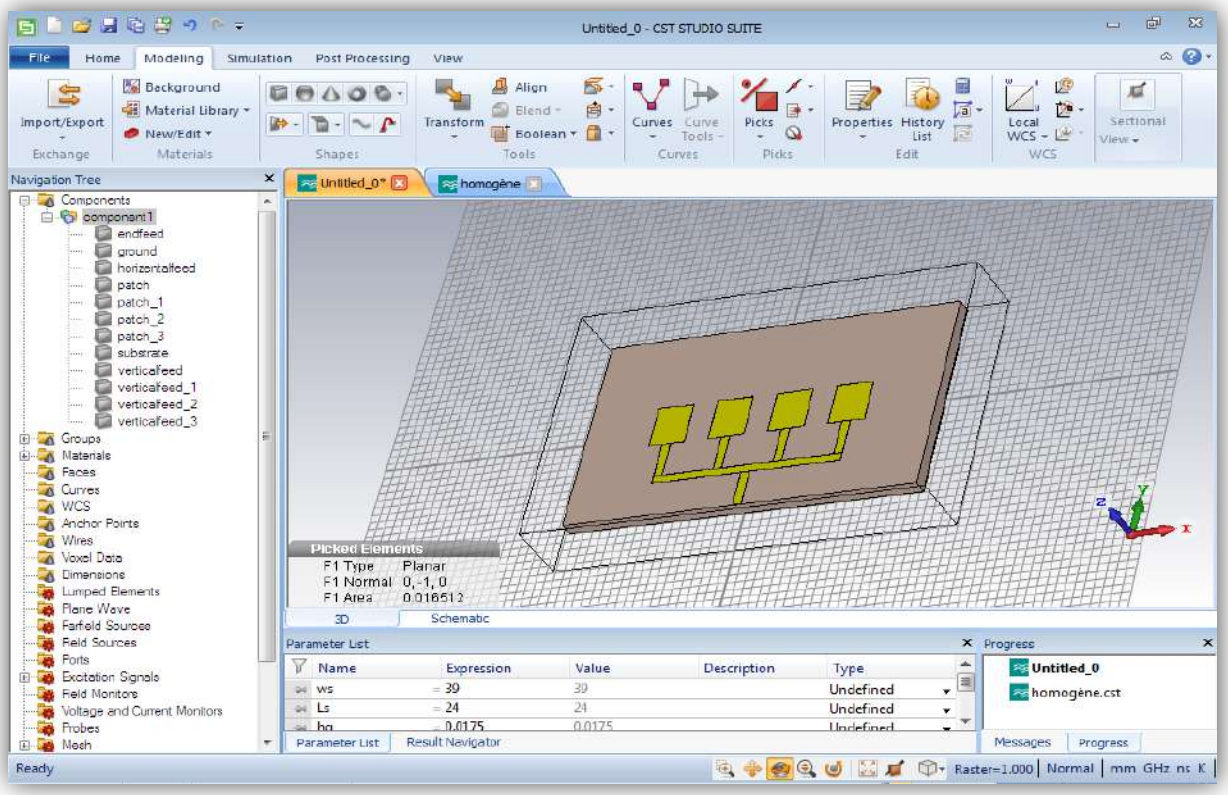




14) Modeling the patch :

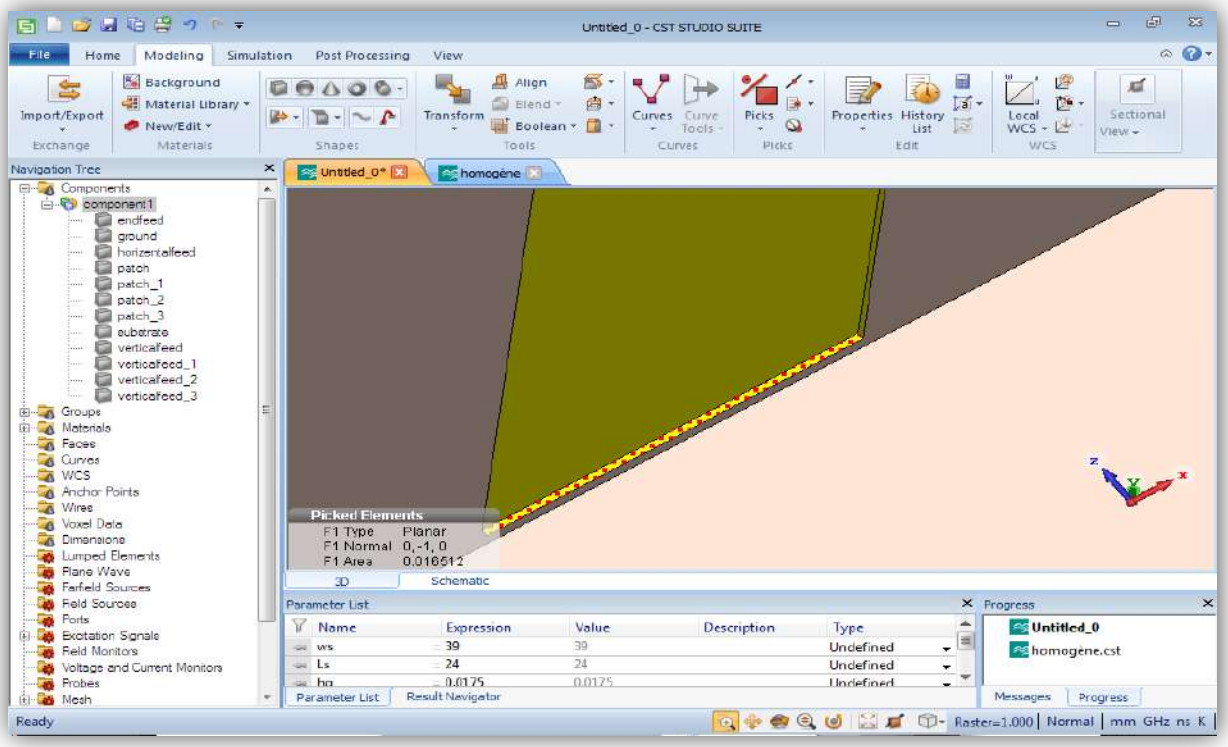


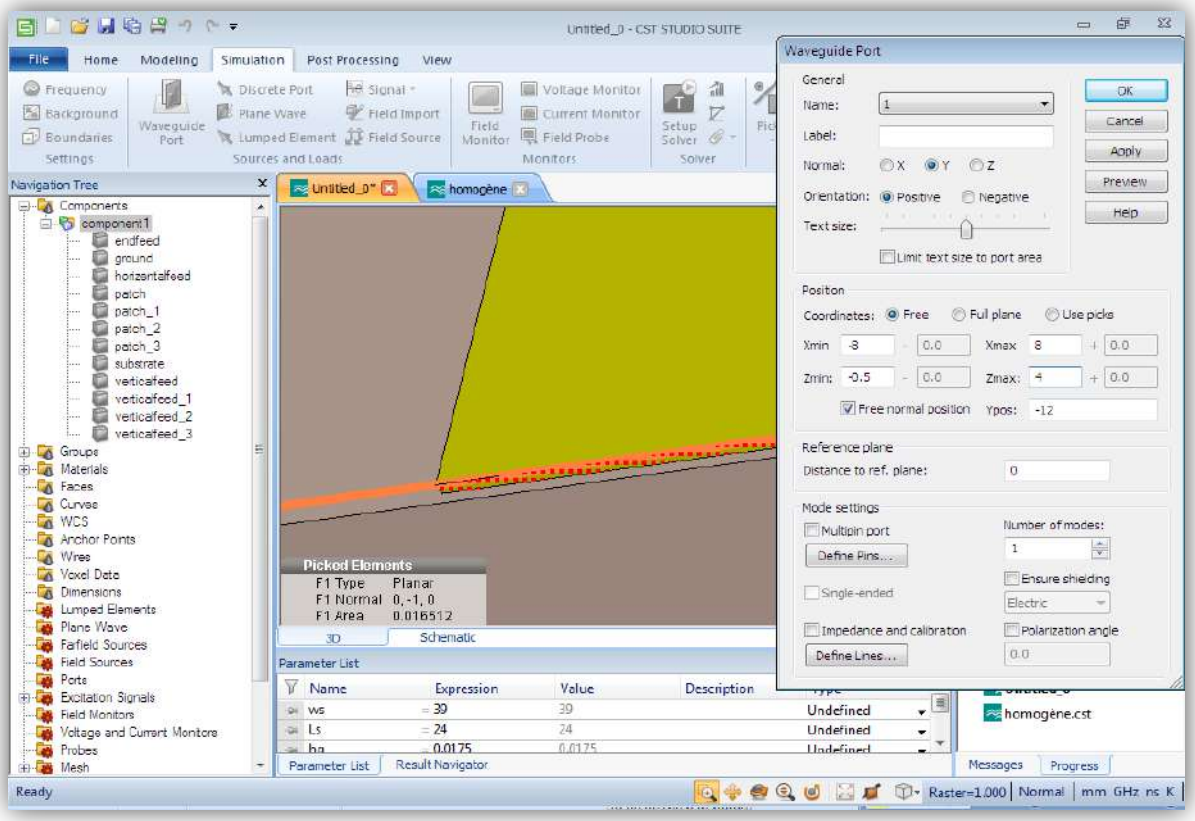


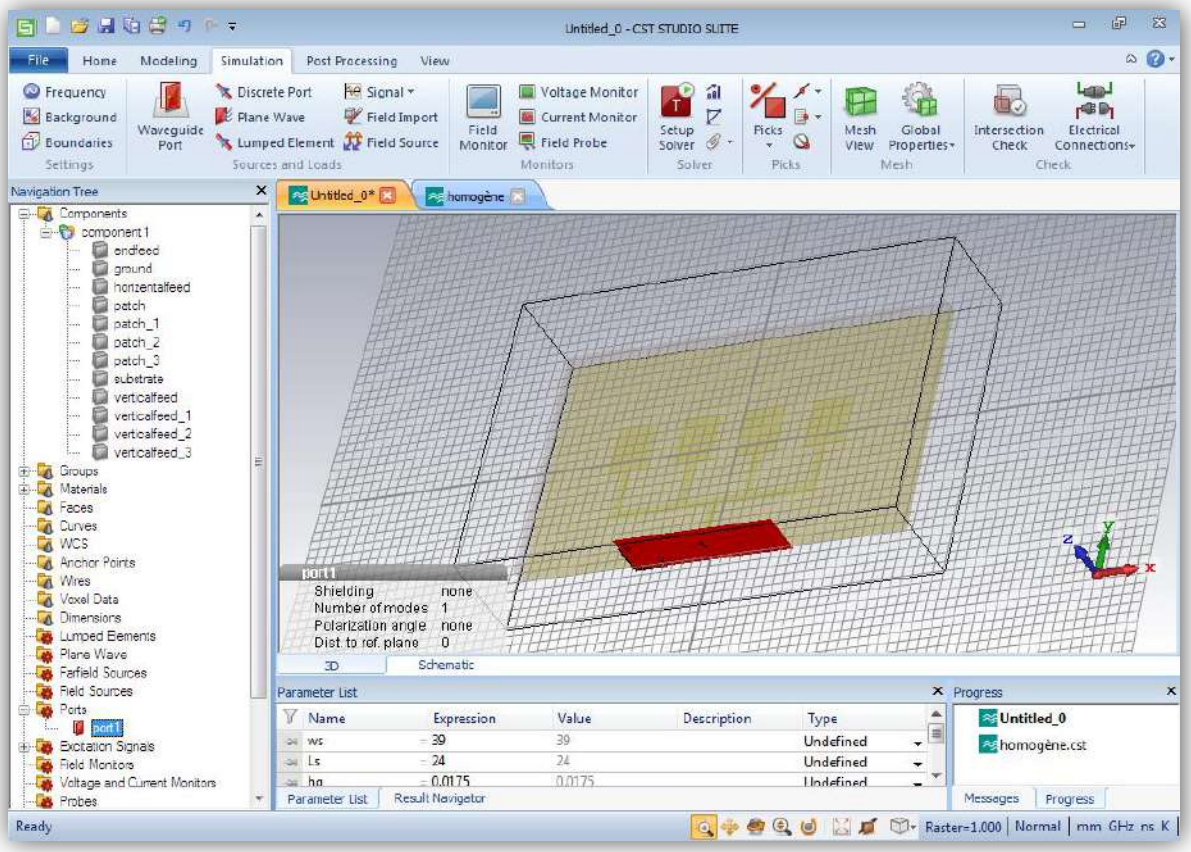


15) Power to the antenna via the guidance port wave:

We click on modeling –picks—pick face at the end of the line. Then we follow the steps described in the following figures




Untitled_0 - CST STUDIO SUITE
File
Home
Modeling
Simulation
Post Processing
View
Waveguide Port
General
Name:
Label:
Normal:
Orientation:
Positive
Negative
Text size:
Limit text size to port area
OK
Cancel
Apply
Preview
Help
Position
Coordinates:
Free
Full plane
Use picks
Xmin
Xmax
Zmin:
Zmax:
Free normal position
Ypos:
Reference plane
Distance to ref. plane:
Mode settings
Multipin port
Define Pins...
Number of modes:
Single-ended
Ensure shielding
Electric
Impedance and calibration
Define Lines...
Polarization angle
Navigation Tree
Components
component1
endfeed
ground
horizontalfeed
patch
patch_1
patch_2
patch_3
substrate
verticalfeed
verticalfeed_1
verticalfeed_2
verticalfeed_3
Groups
Materials
Faces
Curves
WCS
Anchor Points
Wires
Voxel Data
Dimensions
Lumped Elements
Plane Wave
Farfield Sources
Field Sources
Ports
Excitation Signals
Field Monitors
Voltage and Current Monitors
Probes
Mesh
Untitled_0*
homogène
Picked Elements
F1 Type Planar
F1 Normal 0, -1, 0
F1 Area 0.016512
3D
Schematic
Parameter List
Name
Expression
Value
Description
Type
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Ls
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Undefined
Result Navigator
Messages
Progress
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Raster=1.000
Normal
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Untitled_0 - CST STUDIO SUITE
File
Home
Modeling
Simulation
Post Processing
View
Frequency
Background
Boundaries
Settings
Waveguide Port
Discrete Port
Plane Wave
Lumped Element
Signal
Field Import
Field Source
Sources and Loads
Field Monitor
Voltage Monitor
Current Monitor
Field Probe
Monitors
Setup Solver
Solver
Picks
Mesh View
Global Properties
Mesh
Intersection Check
Electrical Connections
Check
Navigation Tree
Components
component1
endfeed
ground
horizontalfeed
patch
patch_1
patch_2
patch_3
substrate
verticalfeed
verticalfeed_1
verticalfeed_2
verticalfeed_3
Groups
Materials
Faces
Curves
WCS
Anchor Points
Wires
Voxel Data
Dimensions
Lumped Elements
Plane Wave
Farfield Sources
Field Sources
Ports
port1
Excitation Signals
Field Monitors
Voltage and Current Monitors
Probes
Untitled_0*
homogène
port1
Shielding none
Number of modes 1
Polarization angle none
Dist to ref. plane 0
3D
Schematic
Parameter List
Name
Expression
Value
Description
Type
ws
Ls
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Undefined
Result Navigator
Progress
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homogène.cst
Messages
Progress
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Raster=1.000
Normal
mm GHz ns K