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Design, Simulation and Fabrication of Millimeter Wave (mm-Wave) Antenna for Next Generation Mobile Communication Networks

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Declaration

This is to certify that the research work was conducted by the following team members in accordance to the guidelines and conditions given by Nigerean Communications Commissions (NCC).

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Abstract

This research is aimed at design, simulation and fabrication of millimeter wave (mm-wave) antenna for next generation mobile communication networks by enhancing the bandwidth of a millimeter wave microstrip patch antenna (MPA) and its array for a 5G mobile communication network. The proposed antenna is designed and fabricated on a Rogers RT Duroid 5880 substrate with a standard thickness of 0.5 mm, a relative dielectric constant of 2.2, and a tangent loss of 0.0009. With a center frequency of 28 GHz, a measured return loss of -21.37 dB, a bandwidth of 1.14 GHz, and a gain of 6.27 dBi, the proposed single element operates in the Local Multipoint Distribution Service band. The proposed antenna is designed and manufactured as an array of 1×2 and 1×4 elements. The 2-element MPA array has a measured bandwidth of 1.207 GHz and a gain of 7.76 dBi, higher than that of a single element. The 4-element MPA array achieved a measured bandwidth of 2.685 GHz and a gain of 9.87 dBi, which is higher than the 2-element and single-element arrays at 28 GHz. This demonstrates that the array of antennas improves gain and bandwidth significantly. Hence, the proposed antenna and array are suitable for 5G mobile communication networks due to their small size.

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Introduction

1.1. Research Background

The rapid increase of mobile data growth and the use of smartphones are creating unprecedented challenges for wireless communication systems. Wireless communications generations from the Automated Maritime Telecommunications System (AMTS)/ Nordic Mobile Telephone (NMT) first generation (1G) through the Long-Term Evolution (LTE) fourth generation (4G) have worked with essentially limited bandwidth. They are limited to a carrier frequency spectrum ranging between 700 MHz and 2.6 GHz. To overcome a global bandwidth shortage to deliver high quality, low latency video and multimedia applications for wireless devices, wireless carriers require support with a new wireless spectrum beyond the 4G standard. Even with the advances of 4G LTE, the network is running out of bandwidth and suffering from traffic growth over the years. A fast growing number of users want more services that consume ever-increasing bandwidth. The solution is to add more bandwidth to wireless networks [1], [2]. MmWave wireless communications is the next breakthrough frontier for wireless networks in the mobile cellular industry, for emerging wireless local area networks, personal area networks, and for vehicular communication [3].

When mobile communications are described, they refer to the overall technology, speed, frequency and system in numeric generations such as 3G, 4G or 5G. Each generation has unique technologies that define it. The evolution of mobile communications is shown in Figure 1.1. The very first generation of a commercial cellular network was introduced in the late 70s with fully implemented standards being established throughout the 80s [4]. The radio signals used by 1G were analogue signals, meaning the voice of a call was modulated to a higher frequency rather than being encoded to digital signals. Analogue signals degrade over time and space meaning that voice data often lacked quality within a call. In comparison, for digital communications, a larger amount of data could be carried effectively. The second generation saw the introduction of GSM (Global System for Mobile Communication) technologies as a standard in the early 90s. It allowed for digital voice and data to be sent across the network and allowed users to roam for the first time. It also used Signalling and Data Confidentially and Mobile Station Authentication to ensure improved security and privacy of telephone calls. The advance in technology from 1G to 2G introduced many of the fundamental services that are still used today, such as SMS, international roaming, conference calls, call hold and billing based on services e.g. charges based on long distance calls and real-time billing. Between the year 2000 and 2003, an upgrade in technologies introduced the packet network, which provided high-speed data-transfer and Internet, and became known as 2.5G. The standards included GPRS (General Packet Radio Service) and EDGE (Enhanced Data Rates in GSM). GPRS supported flexible data transmission rates and provided a continuous connection with the network. It also allowed the service provider to charge for the quantity of data sent, rather than their connection time. Introduced commercially in 2001, the goals set out for the third generation (3G) mobile communications were to facilitate greater voice and data capacity, support a wider range of applications and increase data transmission at a lower cost [5]. For the first time, this generation supported high-speed Internet access as well as fixed wireless Internet access and allowed for video calls, chatting and conferencing, mobile TV, video on demand services, navigational maps, email, mobile gaming, music and digital services such as movies. Significantly, greater security features were introduced within 3G, including Network Access, Domain Security and Application Security. Initiated in 2010, 4G is an all IP based network system [6]. Its purpose was to provide high speed, high quality and high capacity to users while improving the security and lowering the cost of the voice and data services, multimedia and Internet over IP. One of the major benefits of an IP based network was that it was able to seamlessly handover, for voice and data to GSM, UMTS and CDMA2000 technologies from the previous different generation infrastructure.

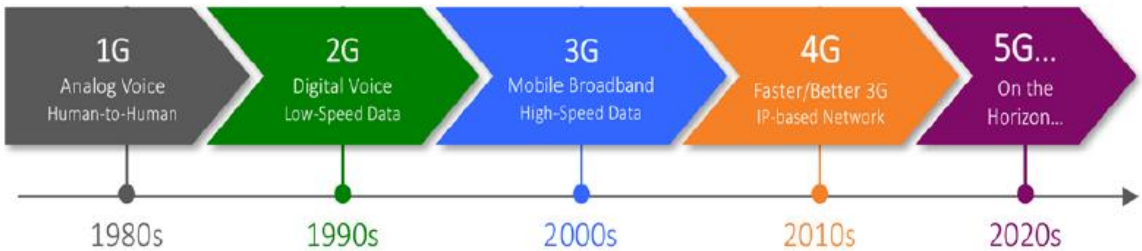

Figure 1.1. Evolution of mobile communication [6].

1.1.1. First Generation Wireless Technology (1G)

1G is the first-generation wireless telephone technology based on analog signal. They were introduced in 1980 and were called analog cell phones. Nippon Telephone and Telegraph (NTT) introduced the first cellular system in the world which became operational in Tokyo, Japan in 1979. The most popular analog systems in Europe were Nordic Mobile Telephone (NMT) and Total Access Communication System (TACS). Along with these two systems, some other technical company introduced analog systems in 1980's in Europe. However, the cellular networks systems were not able to interoperate between countries, offered handover and roaming capability [7]. The key downside of First-Generation mobile technology is the failure to interoperate between different countries. In addition, 1G has other drawbacks such as low capacity-unreliable handoff system, poor voice links. Also, there was no security since voice calls were used to play back in wireless towers making these calls susceptible to undesirable persons. The first 1G standard in USA was AMPS, launched in 1982. Federal Communication Commission (FCC) allocated a 40 MHz channel within the 800-900 MHz frequency range for this system. AMPS was allocated a supplementary 10 MHz bandwidth, called expanded spectrum (ES) in 1988. Italy, France and UK used communication systems called RTMI, Radio-Comm and

YACS respectively. A telecom standard branded as C-450 was introduced in West Germany, Portugal and South Africa. First Generation system replaced 0G system, whose features includes mobile radio telephones and technologies as Advanced Mobile Telephone System (AMTS), Mobile Telephone System (MTS), Push to Talk (PTT), and Improved Mobile Telephone Service (IMTS).

- ✓ Established in 1980s and finalized in early 1990s
- ✓ Supported data transfer speed up to 2.4 kbps
- ✓ Advance mobile phone system (AMPS) was first introduced by the USA and is a first-generation mobile system.
- ✓ It permits the users to initiate voice calls within only one country [7].

1.1.1.1. Key features (technology) of 1G system

Key features of 1G system given below

- ✓ Frequency 800 MHz and 900 MHz
- ✓ Bandwidth: 10 MHz (666 duplex channels with bandwidth of 30 KHz)
- ✓ Technology: Analogue switching
- ✓ Modulation: Frequency Modulation (FM)
- ✓ Mode of service: voice only
- ✓ Access technique: Frequency Division Multiple Access (FDMA)

1.1.1.2. Disadvantages of 1G system

Disadvantages of 1G system given below

- ✓ Poor voice quality due to interference
- ✓ Poor battery life
- ✓ Large sized mobile phones (not convenient to carry)

- ✓ Less security (calls could be decoded using an FM demodulator)
- ✓ Limited number of users and cell coverage
- ✓ Roaming was not possible between similar systems [8].

1.1.2. Second Generation Wireless Technology (2G)

2G is the Second-Generation wireless network, established on digital technologies installed in 1990s. 2G was introduced in Finland in 1991. It provided services for instance Short Message System (SMS), picture messages and Multimedia Message System (MMS). As in 2G, text messages and audio signals are digitally encoded, which permits for the transmission of data in such a way that only desired receiver can receive and decode it. 2G provides greater security for both sender and receiver. To compress and multiplex Digital signal CODEC (compression decompression algorithm) is used in 2G. TDMA and CDMA were used as digital multiple access technology in 2G system. TDMA splits signal in time slots whereas CDMA assigns each user a distinct code to communicate over a multiplexed channel. TDMA technologies includes Global System for Mobile Communications (GSM), Personal Digital Cellular (PDC) IS-136, and iDEN in the Digital Enhanced Cordless Telecommunications (DECT) standard for portable mobile phones. GSM was the first 2G System. It is the most appreciated mobile standard of all mobile wireless technologies deployed in around 212 countries in the world. International roaming between different mobile phone operators was introduced first by GSM technology which allows the users to use their mobile phones in many countries. TDMA technology is used in GSM to multiplex up to 8 calls per channel in the 900 MHz and 1800 MHz frequency bands. It delivers voice signals along with circuit switched data at speed up to 14.4 kbps. FCC also auctioned a new block of spectrum in the 1900 MHz band in the USA. During last 20 years, this technology has been constantly developed to provide better services. Some new technologies have been industrialized based on the original GSM, prominent to some advanced system, identified as 2.5 generation (2.5 G) Systems [7].

1.1.2.1. Key features of 2G system

Key features of 1G system given below,

- ✓ Digital system (switching)
- ✓ SMS services is possible
- ✓ Roaming is possible
- ✓ Enhanced security
- ✓ Encrypted voice transmission
- ✓ First internet at lower data rate
- ✓ Disadvantages of 2G system
- ✓ Low data rate
- ✓ Limited mobility
- ✓ Less features on mobile devices
- ✓ Limited number of users and hardware capability [8].

1.1.3. Third Generation Wireless Technology (3G)

Telecommunication standards group 3G is used to define the third generation of wireless communication standards, overriding 2.5G, and preceding 4G. International Telecommunication Union (ITU) framed a plan to employ the worldwide frequency band of 2000 MHz, which will be able to support a single, ever-present wireless network standard for all countries in the world. The plan is known as "International Mobile Telephone 2000" or IMT-2000 Standard. There are three type of multiple access technology-CDMA 2000: It is proposed by North America wireless Telecommunication standards groups based on Code Division Multiple Access technology. Its channel width is 1.25 MHz and speed are up to 144 Kbps. WCDMA (UMTS): WCDMA service FOMA was launched by NTT Do Como in Japan for the first time in the world commercially in

2001. It is elaborated as Wideband Code Division Multiple Access. Its channel width is 5 MHz and speed are up to 2 Mbps. TD-SCDMA: China wireless Telecommunication standards group proposed the Time Division Synchronous Code Division Multiple Access technology for use in 3G [5]. Third Generation Partnership Project (3GPP) has continued that project by formulating a wireless system that achieves the specification of IMT-2000 standards. The third generation or 3G wireless technology came into services in the year of 2000.

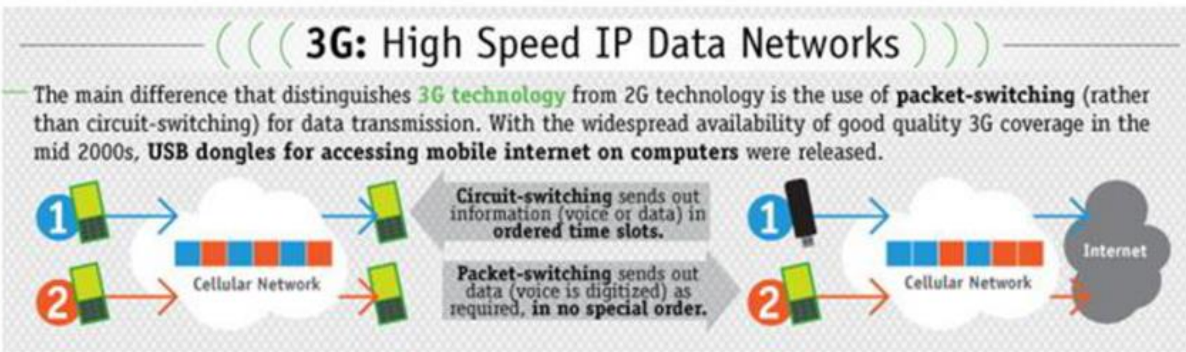

Figure 1.2: 3G vs 2G Communication [9].

Previous technology supported data transmission speed of 144Kbps as peak whereas 3G has increased it to 2 Mbps. Smart phone or multimedia cell phone is required to get services of 3G technology. Bandwidth and data transfer rate were increased in 3G to facilitate web-based application, audio, and video files. conferencing, entirely in a portable wireless environment. Figure 1.2 shows 3G vs 4G communication. Network operators are enabled to offer their users a broader range of more progressive facilities by achieving better network capacity through enhanced spectral efficiency with the deployment of 3G technologies. 3G system services comprises of wide area wireless voice call, video calls, mobile television, broadband wireless data, GPS service and video. This network has the improvements over 2.5G network and previous given below [7]:

- ✓ Numerous times higher data transfer speed.

- ✓ Upgraded audio and video streaming
- ✓ Video conferencing facility

- ✓ greater speed in WAP and Web browsing
- ✓ IPTV (TV through the Internet) support

1.1.3.1. Key features of 3G system

Key feature of 3G system is given below

- ✓ Higher data rate
- ✓ Video calling
- ✓ Enhanced security, a greater number of users and coverage
- ✓ Mobile app support
- ✓ Multimedia message support
- ✓ Location tracking and maps
- ✓ Better web browsing
- ✓ TV streaming
- ✓ High quality 3D games [8].

1.1.3.2. Disadvantages of 3G systems

Disadvantage of G system is written below

- ✓ Expensive spectrum licenses
- ✓ Costly infrastructure, equipment's and implementation
- ✓ Higher bandwidth requirements to support higher data rate
- ✓ Costly mobile devices
- ✓ Compatibility with older generation 2G system and frequency bands [8].

1.1.4. Fourth Generation Wireless Technology (4G)

The main concept of 4G is inter-operability between diverse categories of networks, to provide high speed data transfer rate for example 100 Mbps as the peak data rate for both the server and the data receiver which are moving at a speed of 60 Kmph. And the data transfer rate should be a maximum of 1 Gbps when the server and the receiver are stationary [7]. Comparison of 4G cell phone generation shown in figure 1.3. Currently deployed mobile networks standards are 4G that have replaced third generation-networks in many countries. In other context, 4G is just an initiative by academics'research. trouble being deployed, and able to meet its predefined performance and throughput. Now we can access the internet by using our cell phone with the assistance of various technologies, like Wi-Max, Wi-Fi, WAP, GPRS, EDGE and Wi-Bro in 3G. But the users are facing problem when they have to developments labs to cope with the limitations and difficulties of 3G, which is having access the internet through the cell phone by using any of these described technologies, the user is stuck when they travel to place where inter-operability in the middle of different networks attains.

4 Cell Phone Generations Compared

	Standards	Technology	SMS	Voice Switching	Data Switching	Data Rates
1G	AMPS, TACS	Analog	No	Circuit	Circuit	N/A
2G	GSM, CDMA, EDGE, GPRS	Digital	Yes	Circuit	Circuit	236.8 kbps
3G	UTMS, CDMA2000, HSPDA, EVDO	Digital	Yes	Circuit	Packet	384 kbps
4G	LTE Advanced, IEEE 802.16 (WiMax)	Digital	Yes	Packet	Packet	up to 1 Gbps

Figure 1.3. 4G cell phone generation compared [9].

When using 4G, the users are able to access the network using any of the previously mentioned technologies even though travelling from one place to another. The issues that are considered to be resolved in 4G mobile network are as below:

i. As per high data transfer rates are send and receive through the phone 4G wireless technology has inserted IP feature in the mobile phone for enhanced security purpose.

ii. In fourth generation wireless standard, the users can download at a data rate of 100 Mbps in mobile access and in case of stationary 1Gbps for local access of mobile network.

iii. OFDMA is a new technology introduced in 4G in place of hybrid technology deployed in 3G with the mixture of IS-95 and CDMA. OFDMA is more efficient than previous TDMA or CDMA.

iv. In OFDMA, data are sent by allocating the channel into a narrow band for better efficiency which is an outstanding feature of fourth generation wireless system.

v. 4G will define it as Wireless Mobile Broadband Access (WMBA) which is in processing in IEEE 802.16e. This indicates for the internet availability. To avoid call interference in case of data download from any website the execution is in development. An extra ordinary step in 4G wireless technology is that it will propose downlink data rate as 128 Mbps and uplink data rate 56 Mbps. The condition for the internet connectivity is the availability of hotspot which is the limitation of the service.

vi. In Parallel with Worldwide Interoperability for Microwave Access (WiMAX), LTE a wireless system for the broadband access is intended to integrate in 4G mobile phones. There is difference between WiMAX and LTE. LTE goes for the IP Address and follows the same TCP/ IP idea inherited from computer networking architecture. It will provide greater security as well as high data transferability, low latency, capability to regulate the bandwidth. 4G or LTE is also compatible with CDMA technology so it is able to back n forth the data in between both networks.

vii. LTE and IEEE 802.16m are the two major wireless standards going to be introduced by 3GPP. Earlier one is approved permission for the more process while it will become a fragment of fourth generation wireless system. IPv6 is permitted by Version as a 4G wireless standard on June 2009 [7].

1.1.4.1. Key features of 4G systems

Key feature of 4G system is given below.

- ✓ Much higher data rates up to 1Gbps
- ✓ Enhanced security and mobility
- ✓ Reduced latency for mission critical applications
- ✓ High definition video streaming and gaming
- ✓ Voice over LTE network VoLTE (use IP packets for voice)

1.1.4.2. Disadvantages of 4G system

Disadvantage of 4G system is given below.

- ✓ Expensive hardware and infrastructure
- ✓ Costly spectrum (most countries, frequency bands are is too expensive)
- ✓ High end mobile devices compatible with 4G technology required, which is costly
- ✓ Wide deployment and upgrade are time consuming [8].

1.1.5. Fifth Generation Wireless Technology (5G)

Fifth generation or 5G is the next generation of wireless technology standards planned to deploy around 2020. 5G is to facilitate wireless networks by delivering enhanced bandwidth, high data transfer rates and lower latency to a billion number of electronic devices. This is one of the most promoted issues in the world of technology which is promising to facilitate the access to self-driving vehicles, virtual reality (VR), and the Internet of Things (IoT). Telecommunication enterprises or regulation bodies for example 3GPP, WiMAX or ITU-R have not finalized any particular specification or official document for 5G yet. 5G technology is supposed to be the perfection level of wireless communication systems in mobile wireless technology.

Wired communication has now come to be almost obsolete. At present Cell phones are not only a serving as a communication tool but also being used for many other purposes. Earlier wireless technologies are facilitating the simplicity of telephone and data sharing whereas fifth generation is bringing a new level and turning the life of human as a real mobile life.

1.1.5.1. Features of 5G

Feature of 5G is given below

- ✓ 1-10Gbps connections to end points in the field.
- ✓ Latency of 1ms
- ✓ 1000x bandwidth per unit area.
- ✓ 10-100x number of connected devices.
- ✓ Availability 99.999 percent.
- ✓ 100 percent coverage.
- ✓ 90 percent saving in system energy usage [8].

This section concludes by with hindsight at existing wireless systems and also briefing the upcoming generation of wireless communication technologies in the table below. In the next years these new technologies have a long approach to travel and exciting and amazing features are destined to roll out to come [10]. Table 1.1 shows generation of communication.

TABLE 1.1 GENERATION OF COMMUNICATION

Generation	Speed	Technology	Time period	Features
1G	14.4 Kbps	AMPS, NMT, TACS	1970 – 1980	During 1G Wireless phones are used for voice only.
2G	9.6/ 14.4 Kbps	TDMA, CDMA	1990 to 2000	2G capabilities are achieved by allowing multiple users on a single channel via multiplexing. During 2G Cellular phonesare used for data also along with voice.
2.5G	171.2 Kbps 20-40 Kbps	GPRS	2001-2004	Internet becomes widespread and data becomes more appropriate. Multimedia services and streaming starts to grow. Cell Phones started to support web browsing, though limited number of cell phones have that facility.
3G	3.1 Mbps, 500-700 Kbps	CDMA-200 UMTS, EDGE	2004-2005	Supports multimedia services together with streaming. Worldwide access and movability across different types of device are made possible such as Telephones, PDA's etc.
3.5G	14.4 Mbps, 1-3 Mbps	HSPA	2006 – 2010	Provides higher throughput and speeds to support higher data

4G	100-300 Mbps. 3-5 Mbps 100 Mbps (Wi-Fi)	WiMax, LTE, Wi-Fi	Now (Read more on Transitioning to 4G)	Speeds for 4G are further increased to keep up with data access demand used by various services. High definition streaming is now supported in 4G. New phones with HD capabilities surface. It gets pretty cool. In 4G, Portability is increased further. World-wide roaming is not a distant dream.
5G	1-10 Gbps	Massive MIMO, Beamforming, mm wave	Deployed	Currently there is no 5G technology deployed. When this becomes available it will provide very high speeds to the consumers. It would also provide efficient use of available bandwidth [7].

The requirement for extremely high throughput and more effective communication technology had already resulted in a significant expansion of wireless communication over time. When comparing fifth-generation (5G) base stations to their fourth-generation (4G) counterparts, for example, mobile devices require higher bandwidth [1]. Improved antenna systems are needed to meet the flexibility standards of designs, high gain, and enhanced bandwidth of operation for 5G. Since 5G communications require higher bandwidth, many frequency bands, including 28 GHz, 38 GHz, V band, and E band (71-76 GHz, 81-86 GHz, and 91-93 GHz), can be utilized [4].

A new age of technical development is being ushered in by 5G. The need for communication is shifting globally, and 5G has the potential to revolutionize civilization. It can be used for applications in autonomous driving, robotics, aviation, and the medical field owing to its data transmission rates of more than 1Gbps [4]. The pioneering spectrum bands for the 5G deployment have been identified as 680 MHz, 3.5 GHz, and 26/28 GHz. To that end, many techniques that can enable 5G communication have been proposed in the literature. The slots technique, antenna array technique, defective ground plane structure, and metamaterial have all been applied to enhance performance parameters to satisfy the demands of 5G technology.

The use of mmWave frequencies is growing in many applications such as automotive anti-collision radar at 77 GHz [7], vehicle-to-vehicle communication [8], high resolution mmWave [9], satellite cross-link communication in space [11], indoor wireless data transmission at 60 GHz, and outdoor millimeter point-to-point backhaul terminals [12]. Figure 1.4 shows mmWave spectrum for the next generation of wireless networks. There is a large amount of unused spectrum at these higher frequencies and it will alleviate concerns about wireless traffic congestion. Furthermore, wireless systems will support mobile data rates of several gigabits per second, which is thousands of times greater than today's cellular and WiFi networks.

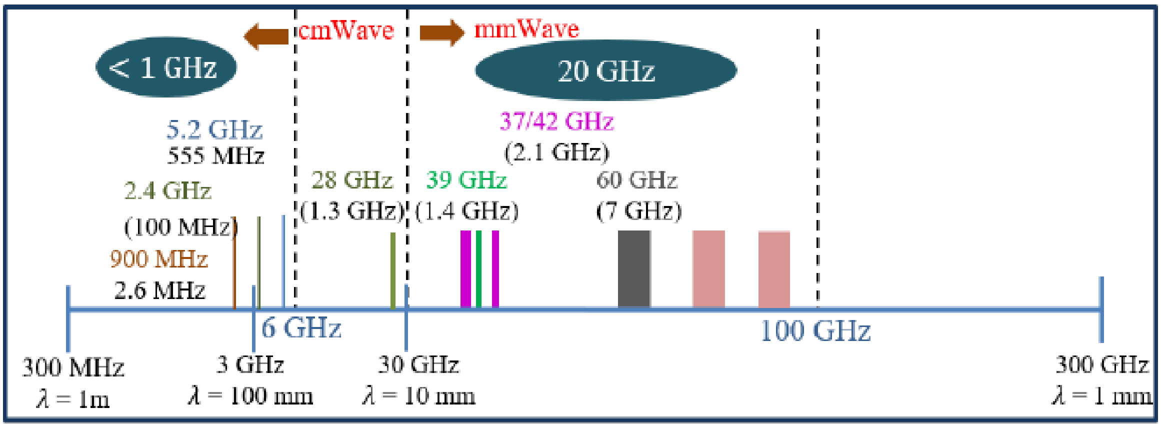

Figure 1.4. MmWave region of the electromagnetic spectrum

1.1.6. Challenges at mmWaves

There are challenges associated with operating in mmWave frequency bands that need to be addressed. In microwave systems, transmission loss is accounted for principally by the free space loss. However, in mmWave bands additional loss factors come into play. As a result of the propagation characteristics at mmWave frequencies, three distinct challenges arise [12]:

- ✓ High level of free space path loss
- ✓ Absorption loss due to atmospheric gases and rainfall

- ✓ Blockage, and scattering effects

1.1.6.1. Free space pass loss (FSPL)

Free-space path loss (FSPL) is more critical in mmWave spectrum than lower frequencies due to a limitation related to their wavelength. For example, comparing FSPL in a 60 GHz system with those in both conventional 2.4 GHz and 5 GHz, the 60 GHz link suffers 27.96 dB and 21.58 dB higher loss than 2.4 GHz and 5 GHz respectively. This loss affects the link budget and becomes a huge challenge when transmitting over a large distance. For a given power, the shorter the wavelength, the shorter the transmission range [13]. In order to improve signal to noise ratio (SNR) at the receiver and thereby increase the transmission range we need to increase the power of the transmitting signal, or use more directive antennas. Due to the limited output power that the current active components can deliver in mmWaves, we can only increase the antennas gains in order to increase the communication distance andcompensate FSPL. Therefore, high gain and low loss antenna is one of the most necessary components of mmWave short and long-range wireless communication systems.

1.1.6.2. Atmospheric losses

Moreover, transmission losses occur when mmWave traveling through the atmosphere. Figure 1.5 depicts average atmospheric losses at mmWave frequencies in dB/km. These losses are greater at certain frequencies. For example, as shown in the figure, absorption loss, due to atmospheric gases such as molecules of oxygen, water vapor and other atmospheric gaseous, reaches its peak value at a frequency of 60 GHz. At mmWaves, the size of raindrops, are significant compared to the wavelength. For raindrops, the size introduces severe energy losses, depending on the magnitude of the rainfall [14]. Considering the amount of the atmospheric losses at mmWaves, these frequencies can be used for various secure short and long rang wireless communications. For instance, due to the high atmospheric absorption at 60 GHz, relatively secure high data rate communications with a low probability of intercept can be performed for short range point-to-point wireless systems such as local area networks. On the other hand, according to Figure 3 the negligible atmospheric absorption at 28 and 38 GHz make these frequencies good candidates for long-range radio links in the emerging 5G cellular.

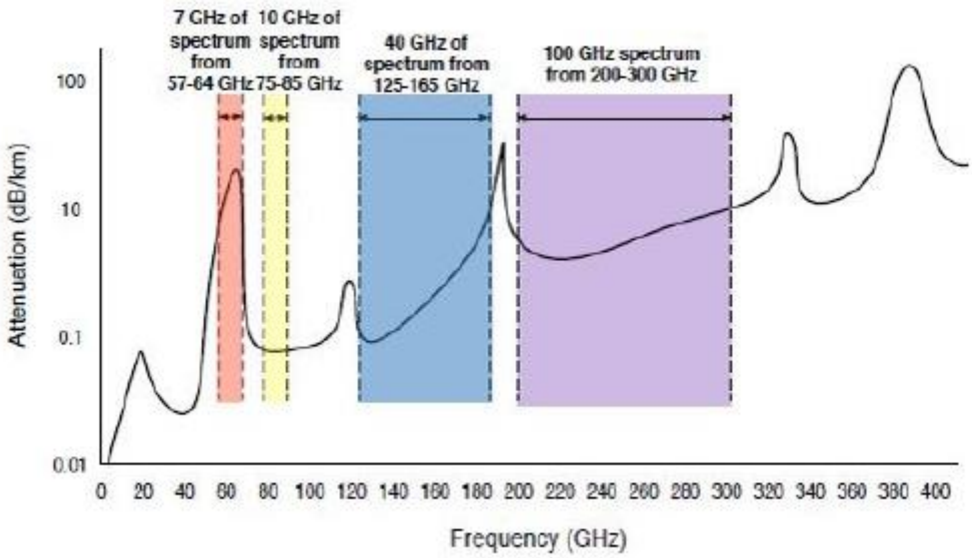

Figure 1.5. Average sea level atmospheric absorption at mmWave frequencies

1.1.7. Blockage, and scattering effects

In addition, in wireless networks, signals at mmWave frequencies due to the very short wavelength are more susceptible to blockage and interference compared to low frequency waves. For example, obstacles such as walls, humans and objects have high penetration losses at mmWave. This means that obstacles can easily disrupt mmWave signals. This forms the major challenge to the use of mmWave frequencies in 5G systems.

1.2. Statement of the Problem

Despite mm-wave have been explored for a while and shows huge potential to achieve multi gigabit wireless communication experience, mm-wave technology presents and faces numerous technical challenges that need to be resolved before its full deployment. The research will explore the solutions possible to remedy the challenges. These challenges include:

1. Channel propagation issues: This is due to the high path loss and transmission loss caused by the absorption of the wave by oxygen and water vapor present in the atmosphere.
2. Antenna technology issues: The antennas to be used for the mm-wave propagation are complex in nature and expensive to design and fabricate.
3. The issue of the choice of integrated circuit (I.C) technology to be used and that is due to lack of a single technology that can simultaneously meet all the requirements.
4. Modulation scheme that will be robust is also an issue since mm-wave radio will be highly dependent on the propagation channel, antenna technology and I.C technology.
5. Size and power consumption of the component electronics.

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1.3. Research Objectives

Based on the challenges identified, this research aims to develop a millimeter wave (mm-wave) antenna for next generation mobile communication networks, through the following objectives:

1. Employing the acceptable concept of mm-wave technology that remedies the channel propagation issues.
2. Employing a modulation scheme that is beyond OFDM suitable for next generation mobile networks.
3. Designing mm-wave antenna based on the employed concept.
4. Simulating the mm-wave antenna that was designed.
5. Optimizing the mm-wave antenna.
6. Fabricating the designed and simulated mm-wave antenna.

Chapter 2

Literature Review

2.1. Introduction

The millimeter-wave (mm-Wave) antenna is an important element of the 5G communication system microstrip antennas have been widely used to date due to their advantages of being compact, lightweight, and simple to integrate which are a good fit for usage in a range of wireless applications, including those for aviation, satellite communication, missiles, and medical applications [15]–[17]. Moreover, it comes with the disadvantage of lower bandwidth which can be enhanced utilizing various designed methods [18] and losses caused by the surface wave; numerous works have been performed to utilize it. Even so, these techniques significantly increase complexity and cost [19]. Similarly, for mm-wave 5G applications, several printed antennas were proposed employing various techniques [18]–[20]. The feeding technique is one of the significant characteristics used to increase impedance bandwidth. However, the feeding method varies depending on antenna fabrication, price, and working mechanism with additional radiation, together with impedance matching [21].

2.2. Antenna Basics

An antenna is a dedicated transducer which transforms radio-frequency (RF) fields into electrical energy or vice-versa. There are two basic types: the receiving antenna, that captures RF energy and delivers alternating current to the equipment, and also the transmitting antenna, that is fed with electrical energy from the equipment and produces radio-frequency field. In wireless applications, the foremost common variety of antenna is that the microstrip patch antenna, used for wireless communications. Microstrip patch antennas are usually sensible solely at microwave frequencies.

2.2.1. Frequency

In normal sense frequency means how frequently occurs a particular event in a particular period. Basically, frequency refers to the number of occurrences of an event in a definite time. From the typical definition, “The number of recurrences of a signal over a defined time period (1 second), is known as frequency. Periodic signal repeats itself after every ‘T’ second called time period. Frequency of periodic signal is nothing but the inverse of time period (T). Figure 2.1 and Figure 2.2 shows frequency diagram. In engineering terminology, frequency is used to identify the rate of oscillatory and vibratory occurrences, for example radio waves, audio signal (sound), mechanical vibrations, and light. The SI (International System) unit of frequency which is entitled by the German physicist Heinrich Hertz is hertz (Hz). One hertz denotes that an event or signal repeats once per second.

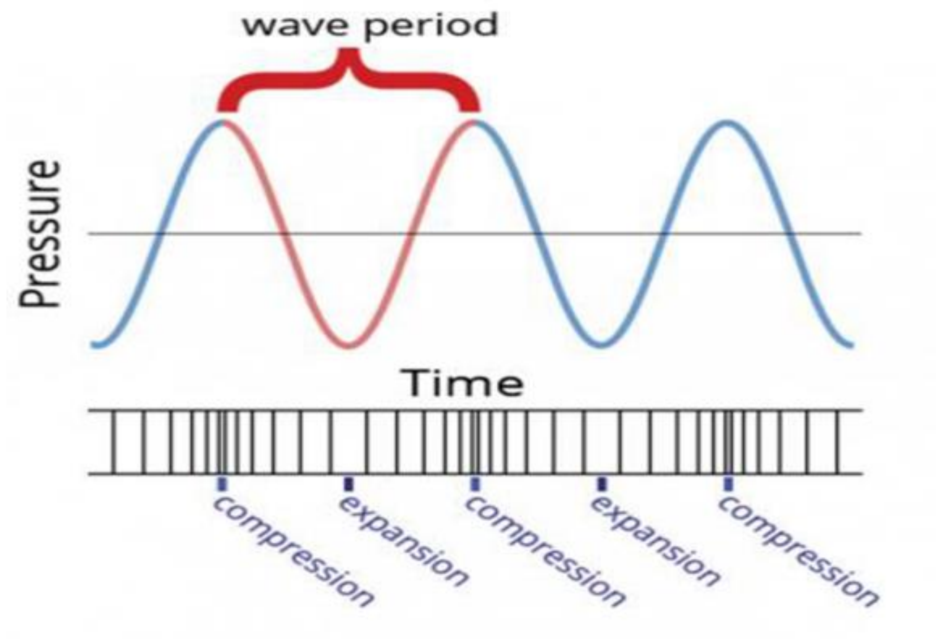


Figure 2.1. Frequency diagram.

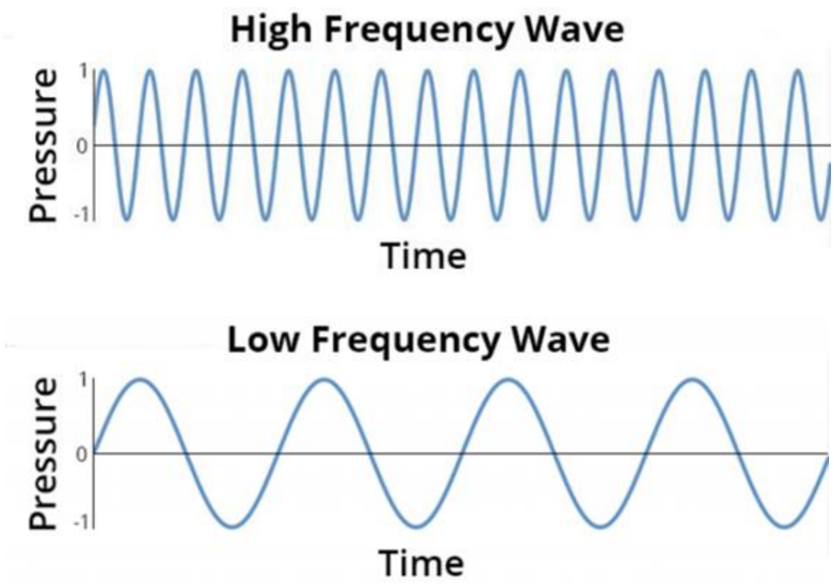


Figure 2.2. High frequency and Low frequency diagram.

2.2.2. Bandwidth

In communication systems, bandwidth is defined as the capacity of a wired or wireless communications system link to transmit the maximum amount of data from one point to another over a computer network or internet connection in a given amount of time, typically in one second. In case of antenna, bandwidth refers to the range of frequency over which the antenna can properly radiate or receive energy. Regularly, bandwidth is one of the most desired determining parameters used to decide upon an antenna. For instance, many antenna types have very narrow bandwidths and cannot be used for wideband operation. Figure 2.3 shows bandwidth in diagram.

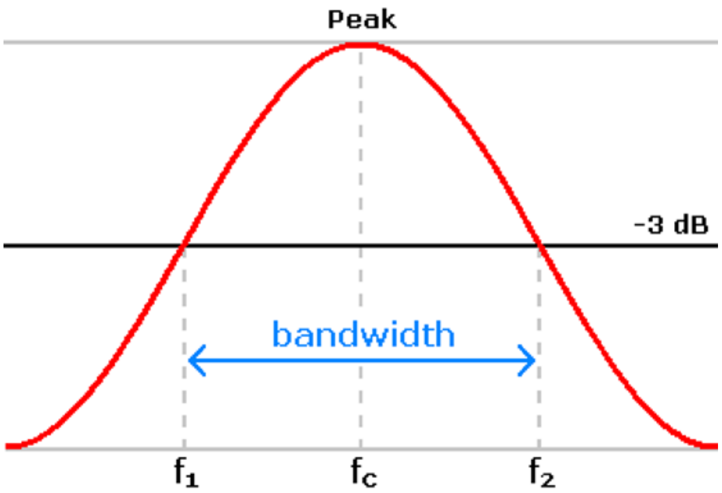


Figure 2.3. Bandwidth diagram.

2.2.3. Input Impedance

The input impedance of an antenna is the ratio of the voltage to the current at the antenna input terminals. It is an important parameter of an antenna, which expresses the resonance of the antenna. There are two parts of the input impedance – real and imaginary. The power that is radiated away or absorbed within the antenna is represented by the real part of the input impedance. The power that is stored in the near field of the antenna is represented by the imaginary part of the input impedance which is known as reflected power. A resonant antenna is a one whose real input impedance and zero imaginary impedance. The input impedance of an antenna is determined by the length and size of that antenna. Impedance is denoted by Z which has a real portion, including the antenna's radiation resistance Rrad and its ohmic losses Rohmic, and a reactive portion X [22].

2.2.4. Impedance Matching

According to the standard definition, "The approximate value of impedance of a transmitter, when equals the approximate value of the impedance of a receiver, or vice versa, it is termed as Impedance matching." In wireless communication, impedance matching is necessary between the antenna and the circuitry. From the theory maximum power transfer, when the impedance of the antenna, the transmission line, and the circuitry match maximum power transfer takes place between the antenna and the receiver or the transmitter. The process of impedance matching of the antenna with the circuitry over a range of frequency is referred to as tuning or matching the antenna. The quality of the match is characterized by VSWR, with Bandwidth referring to the range of frequency that the antenna impedance is close to 50 Ohms for a given VSWR. A resonant device is one, which yields better output at certain narrow band of frequencies. Antennas are such resonant devices whose impedance if matched, delivers a better output.

Necessity of impedance matching given below.

1) The power from the source will be effectively delivered to the feedline, if the feedline impedance matches the source impedance.
2) The power from the feedline will be effectively delivered to the antenna, if the antenna impedance matches the feedline impedance.
3) For a receiver antenna, antenna's output impedance should match with the input impedance of the receiver amplifier circuit.
4) For a transmitter antenna, antenna's input impedance should match with transmitter amplifier's output impedance, along with the transmission line impedance [23].

2.2.5. Directivity and Gain

The ability of an antenna to radiate energy in a particular direction when transmitting, or to receive energy better from a particular direction when receiving is called directivity. And gain is usually defined as the ratio of the power produced by the antenna from a far-field source on the antenna's beam axis to the power produced by a hypothetical lossless isotropic antenna, which is equally sensitive to signals from all directions. There is a relationship between gain and directivity.

This relationship is understood by the phenomena of increased directivity when comparing a light bulb to a spotlight. A 100-watt spotlight will provide more light in a particular direction than a 100-

watt light bulb and less light in other directions. It can be said the light bulb has less "directivity" than the spotlight. The spotlight is comparable to an antenna with high directivity. Gain is the practical value of the directivity. Mathematically gain equals to the multiplication of directivity and efficiency. The relation between gain and directivity includes a new parameter (η) which is known as the efficiency of the antenna [24]. Figure 2.4 shows Directivity and Gain.

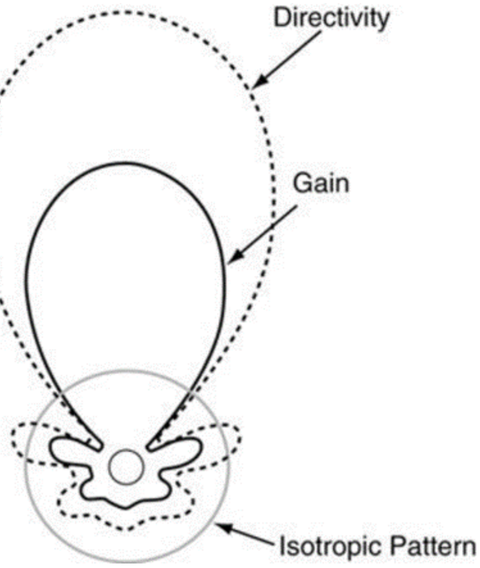


Figure 2.4. Directivity and Gain.

2.2.6. Radiation Pattern

In the field of antenna design the term radiation pattern (or antenna pattern or far field pattern) refers to the directional (angular) dependence of the strength of the radio waves from the antenna. Radiation pattern describes the relative strength of the radiated field in various directions from the antenna at a constant distance. The radiation pattern is a "reception pattern" as well, since it also describes the receiving properties of the antenna. The radiation pattern is three-dimensional, but it is difficult to display the three-dimensional radiation pattern in a meaningful manner. Figure 2.5 shows radiation pattern. It is also time-consuming to measure a three-dimensional radiation pattern. Often radiation patterns measured are a slice of the three-dimensional pattern, resulting in a twodimensional radiation pattern which can be displayed easily on a screen or piece of paper. These pattern measurements are presented in either a rectangular or a polar format [25].

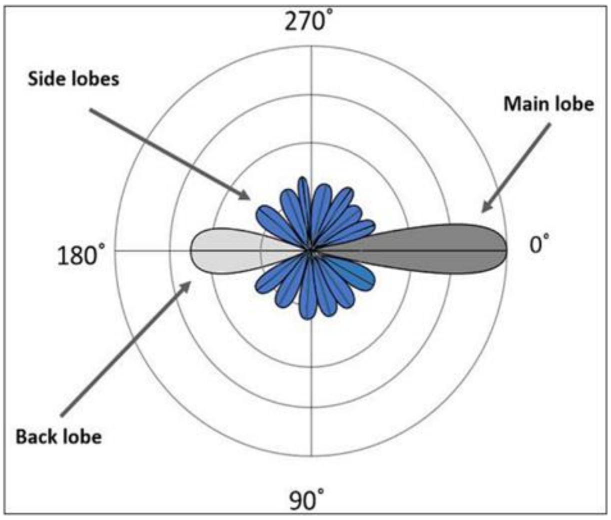


Figure 2.5. Radiation pattern.

2.2.7. Voltage Standing Wave Ratio (VSWR)

VSWR (Voltage Standing Wave Ratio) is a measure of how efficiently radio-frequency power is transmitted from a power source, through a transmission line, into a load. In other words, the ratio of maximum power to minimum power in the wave can be measured and is called the standing wave ratio (SWR). In term of voltage, the ratio of the reflected voltage over the incident voltage is called VSWR. The VSWR is always a real and positive number for antenna. The smaller the VSWR is, the better the antenna is matched to the transmission line and the more power is delivered to the antenna. The minimum VSWR is 1. In this case, no power is reflected from the antenna, which is ideal case [26]. Figure 2.6 shows VSWR.

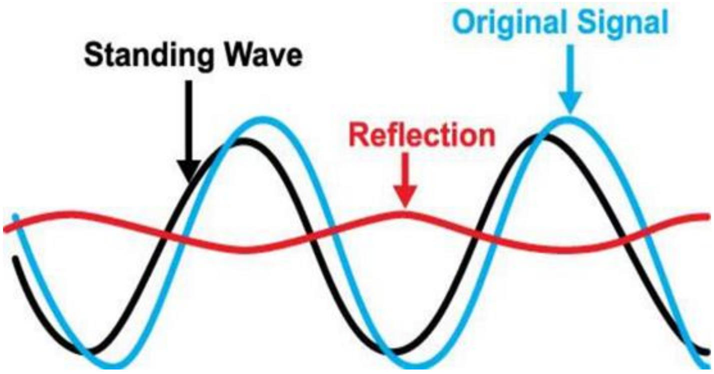


Figure 2.6. VSWR.

2.2.8. Return Loss (RL)

An antenna's Return Loss is a figure that indicates the proportion of radio waves arriving at the antenna input that are rejected as a ratio against those that are accepted. It is expressed in decibels (dB) relative to a short circuit (100 percent rejection). Return loss (RL) is another way of expressing mismatch between the antenna and the feedline. It is algorithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna from the transmission line. The RL is directly related with the VSWR. In practice, the most commonly quoted parameter in regards to antennas are S_{11}. S_{11} is actually nothing but the return loss (RL). If S_{11} = 0 dB, then nothing is radiated and all the powers reflected from the antenna. If S_{11} = -6 dB, this implies that if 3 dB of power is delivered to the antenna, -3 dB is the reflected power. The acceptable VSWR of less than or equal to 2 corresponds to a RL or S_{11} of -9.5 dB or lower.

2.2.9. Polarization

The polarization of an antenna is determined by the electric field of the wave emitted by the antenna. Specifically, the magnitude and phase of the electric field dictate the antenna's polarization. If the magnitudes and phases of the electric field components are equal, the antenna is linearly polarized. If the magnitudes are equal, but the phases differ by 90 degrees, the antenna is circularly polarized. In order for two linearly polarized antennas to communicate with each other, their projected electric fields must be aligned. A circularly polarized antenna however, can communicate with any linear antenna regardless of its orientation. Each polarization type has its advantage; where a circular antenna is orientation insensitive, a linear antenna radiates higher power because all the power is directed in one direction as opposed to being split among the two components. Depending on the application, a reader antenna is either linear or circular, and ideally, the tag antenna should be circularly polarized such that it can be read from any orientation [27]. Figure 2.7 shoes three type of polarization.

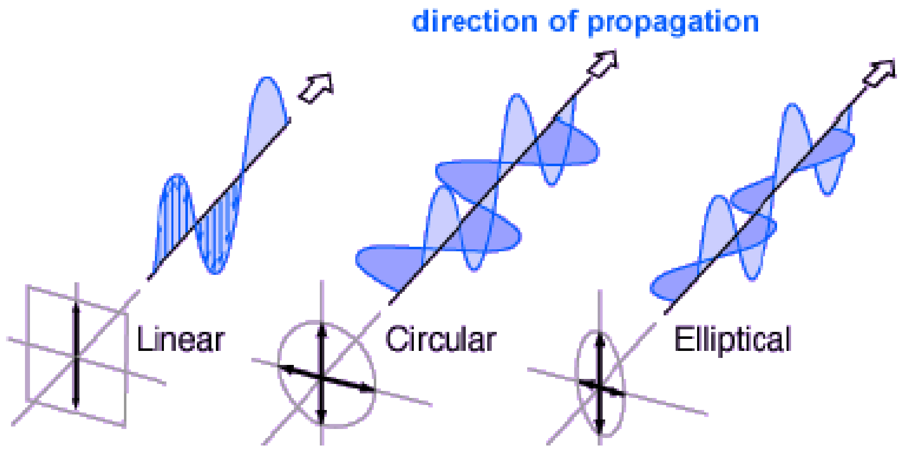


Figure 2.7. Polarization Linear, Circular, Elliptical.

2.3. Microstrip Antenna

A microstrip patch antenna consists of a radiating patch on one side of a dielectric substratewhich has a ground plane on the other side as shown in Figure 2.8. The patch is generally made of conducting material such as copper or gold and can take any possible shape. The radiating patch and the feed lines are usually photo etched on the dielectric substrate. In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular, and elliptical or some other common shape. For a rectangular patch, the length (L) of the patch is usually $0.3333\lambda_0 < L < 0.5\lambda_0$, where λ_0 is the free-space wavelength. The patch is selected to be very thin such that $t \ll \lambda_0$ (where tis the patch thickness). The height h of the dielectric substrate is usually $0.003\ \lambda_0 \leq h \leq 0.05\ \lambda_0$. The dielectric constant of the substrate (εr) is typically in the range $2.2 \leq \varepsilon r \leq 12$.

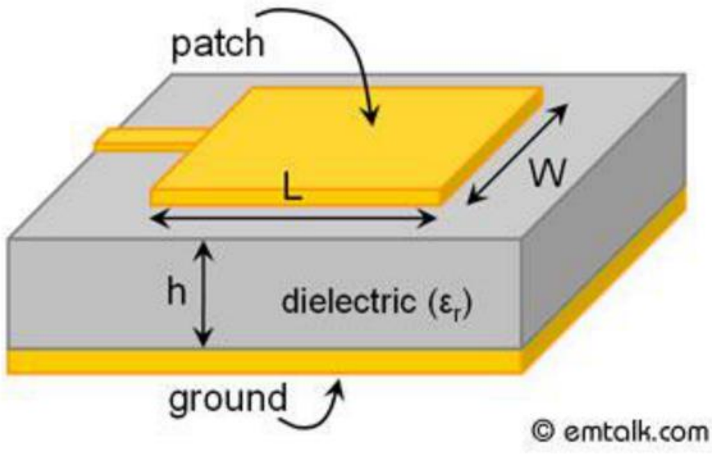


Figure 2.8. Structure of a Microstrip Patch Antenna [28].

Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation. However, such a configuration leads to a larger antenna size. In order to design a compact Microstrip patch antenna, higher dielectric constants must be used which are less efficient and result in narrower bandwidth [28].

2.3.1. Microstrip antenna Feed Techniques

Different type microstrip antenna feed techniques are given below,

1) Microstrip Line Feed
2) Coaxial / Probe Feed
3) Aperture Coupled Feed
4) Proximity Coupled Feed

2.3.1.1. Microstrip Line Feeding

In this type of feeding a microstrip transmission line is etched directly to the edge of patch which remains the total structure in same plane. Figure 2.9 shows microstrip feed line.

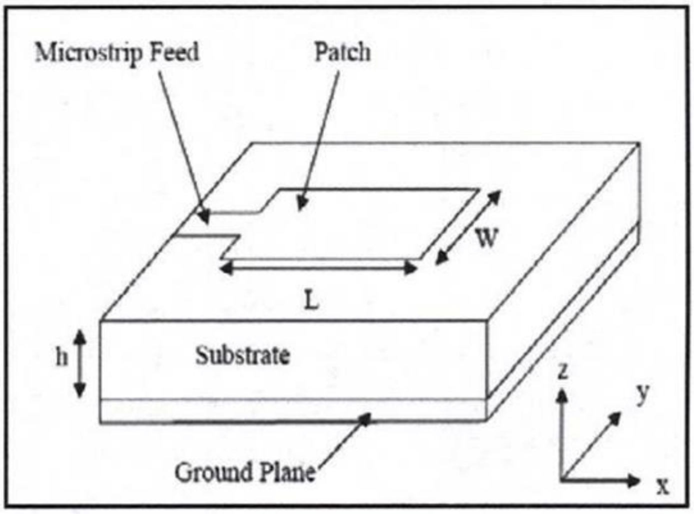


Figure 2.9. Microstrip Line Feeding [29].

2.3.1.2. Coaxial or Probe feeding

The inner conductor of coaxial connector is passing through the substrate and is soldered to the radiating patch, while the outer conductor is connected to the ground plane. Coaxial feeding shown in figure 2.10.

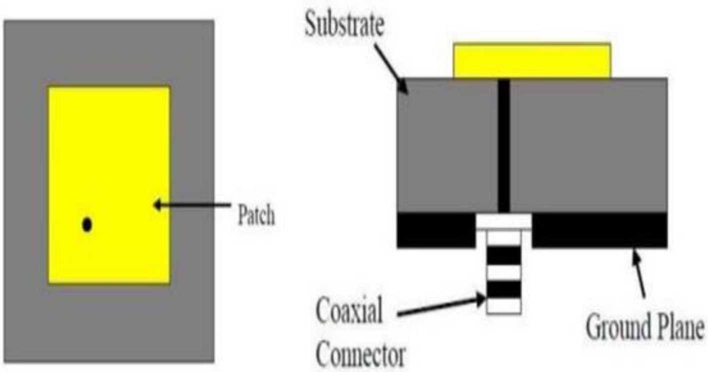


Figure 2.10. Coaxial / Probe Feeding [29].

2.3.1.3. Aperture Coupled Feed

In this type of feed, the aperture coupling consists of two substrates separated by a ground plane. The ground plane is separated the radiating patch and microstrip line which locate at the bottom of lower substrate. The coupling is achieved through an electrically small aperture or slot cut in the ground plane. Figure 2.11 shows aperture-coupled feed.

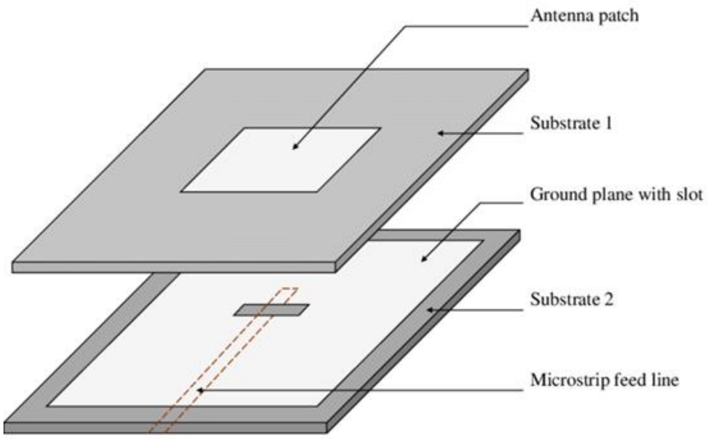


Figure 2.11. Aperture-Coupled Feed [29].

2.3.1.4. Proximity Coupled Feed

It's also called Electromagnetically Coupled ECMSA. It’s also consisting of two substrates. The microstrip feed line is locating between two substrates and the radiating patch is located in the top of upper substrate.

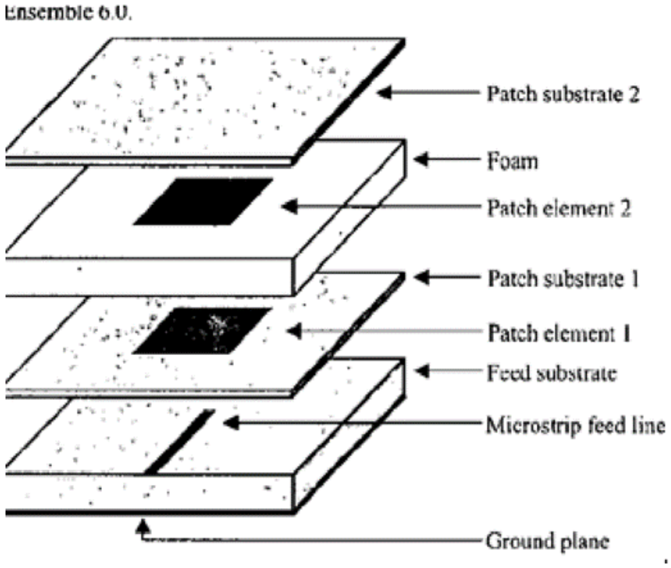


Figure 2.12. Proximity Coupled Feed [29].

2.3.2. Advantages and Disadvantages of Microstrip Antenna

Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore, they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc. The telemetry and communication antennas on missiles need to be thin and conformal and are often microstrip patch antennas.

Some advantages of the microstrip antenna are given below:

1) Microstrip antennas are lightweight and low volume.
2) They can be fabricated at low cost, hence can be manufactured in large quantities.
3) They have Low profile planar configuration, which can be easily made conformal to host surface.
4) Supports both, linear as well as circular polarization.
5) Microstrip antennas can be easily integrated with microwave integrated circuits (MICs).
6) They are Capable of dual and triple frequency operations.
7) They mechanically robust when mounted on rigid surfaces.

Some disadvantages of the Micro-strip antenna are given below:

1) Microstrip antenna has narrow bandwidth.
2) Their efficiency is low.
3) They are of low gain.
4) They suffer extraneous radiation from feeds and junctions.
5) Poor end fire radiator except tapered slot antennas.
6) Their power handling capacity is low.
7) Surface wave excitation.

Microstrip patch antennas have a very high antenna quality factor (Q). Q represents the losses associated with the antenna and a large Q leads to narrow bandwidth and low efficiency. Q can be reduced by increasing the thickness of the dielectric substrate. An increasing fraction of the total power delivered by the source goes into a surface wave. This surface wave contribution can be counted as an unwanted power loss since it is ultimately scattered at the dielectric bends and causes degradation of characteristics [30].

2.4. Techniques of Enhancing Antenna Performance

The performance metrics of an MPA includes return loss, gain, bandwidth, Voltage standing ratio and radiation efficiency. Several techniques have been employed for the enhancement of performance parameters such as introduction of slots of different shapes [31], defected ground plane structure [32], metamaterial [33], increasing substrate height [34], variation of dielectric constant [35],and antenna array. This section will present a review on different researches that employ each of these methods with limitation to 5G application.

2.4.1. Introduction of slots of different patch shapes

Slots of various shapes can be introduced into the patch so as to improve antenna performance.

Authors in [36] designed and fabricated a 28 GHz U-slot MPA for 5G applications. U shaped slots were cut on the patch so as to enhance the bandwidth and frequency response. The antenna was fabricated using Roger RO 4350 substrate with a dielectric constant of 3.66 and microstrip coaxial feeding line was used and HFSS simulation software. The gain obtained was 4.06 dB, VSWR of 1.02 and S_{11} of -20 dB. The authors were however silent about the bandwidth performance. Surajo et al 2019 also designed and simulated a single feed dual band MPA operating at 28 GHz and 38 GHz frequency bands for 5G mobile applications. An inverted U-slot was introduced in the radiator so as to achieve the dual band and also to enhance the bandwidth. The antenna was designed on an FR4 substrate with a compact size of 8x8 mm^2. Wide operation bandwidth was realized with about 1.43 GHz from (27.27 GHz-28.70 GHz) and 3.54 GHz for (35.56 GHz-39.12 GHz) respectively. Similarly, a gain of 2.7 dB and 6 dB was realized for the lower frequency band and upper frequency band respectively. Another researcher [37] designed a millimeter wave inverted U-slot antenna for 5G applications. The antenna was designed and simulated using Rogers R04350B substrate with a dimension of 15.8 x 13.1 mm^2. It consists of an inverted U-slot instead of a simple U-slot and parasitic patches with a coaxial line feed. Simulation results showed that resonant frequency decreases on increasing the slot length and directly proportional to the slot width and feed length. A gain of 4.92 dB, VSWR of 1.2 and the authors were silent about the bandwidth. The use of different shapes on the patch of the antenna has also proved to be another promising technique of enhancing the antenna bandwidth. Work in [38] designed an E-band slotted MPA for 5G broadband applications. The antenna was designed for a resonant frequency of 85 GHz on an RT 6006 substrate with copper patch material and a bandwidth of 2.902 GHz was realized. The gain and the bandwidth could be enhanced. Similarly, [39] designed a single band MPA at 60 GHz for 5G millimeter wave applications. Which consists of E and H slots loaded on the radiating patch with microstrip feeding line using RT 5880 substrate. Results obtained showed return loss of 40.99 dB at 60 GHz with a gain of 5.48 dB and a bandwidth of 4.028 GHz. In another work by [40] It could be seen that the effect of introducing the slots have significantly enhance the antenna bandwidth. Defected ground plane: Modifications of the ground plane of the antenna has also shown to improve the antenna performance as shown by [41]. A novel MPA with helipad like ground modification for lower 5G frequency spectrum of 3 GHz which was designed and fabricated on FR4 substrate. Results obtained showed significant bandwidth improvement which is 18 times larger than the conventional MPA with a full ground plane. Another research was reported by [42] in which the DGS structure enhanced the antenna bandwidth.

2.4.2. Metamaterial

The use of metamaterial has been employed to improve antenna performance in terms of gain and efficiency. This is proposed [43] in which a multiband meta material based antenna operating at 3.6 GHz, 14.33 GHz and 28.86 GHz frequency bands respectively. Rogers 4003 dielectric substrate with a truncated ground plane was used. A metamaterial acting as a high impedance surface was used as a reflector. The results showed significant improvement for all the three bands as follows: {2.76-6.47, 4.83-6.71 and 7.52-7.73} respectively.

2.4.3. Increasing substrate height

A study has been reported by [44] on the effect of changing the substrate height and its effect on antenna performance parameters. The antenna was designed on an RT Rogers 5880 Duroid substrate with a dimension of 19mm x 19mm and 9.5mm x 9.5mm and a coaxial feeding technique. A square shaped antenna with a resonance frequency of 10 GHz was designed in four different variations by changing the height of the substrate from 0.5 mm to 1.6 mm. Simulation results obtained showed a gain of 5.21 dB, 6.11 dB, 9.48 dB and 5.69 dB respectively as the height of the substrate was increased. VSWR was obtained for the four different modes as 1.003, 1.02, 1.78 and 1.66 respectively. Similarly, bandwidth realized for the four different modes are 165 MHz, 198

MHz, 79 MHz and 88 MHz respectively. Resonant frequencies obtained were 29.46 GHz, 10.37 GHz, 10.35 GHz and 2.45 GHz for the four different modes. Based on the results obtained, it could be deduced that as the substrate thickness increases the resonance frequency decreases while the bandwidth increases. Conclusively the first modified antenna gave the best antenna performance suitable for 5G applications.

2.4.4. Antenna array

Several works have been reported on the use of antenna array in order to enhance the antenna performance. Authors in [45] designed and modified serial patch antenna array for 28 GHz mm wave applications. In [46] designed and implemented for the 5G wireless standard using HFSS at 10.11 GHz and obtained a bandwidth of 380 MHz. Similarly, work in [47] simulated an end-fire phase array 5G antenna with the Arlon substrate and obtained good performances in the 28 GHz and 38 GHz bands. [48] proposed a 2 by 2 U-slotted array antenna operating at 28 GHz for the broadband communication system and a bandwidth of 3.35 GHz and a gain of 13dBi was obtained. Similarly, [49] performed on the sloped substrate of mm wave MPA array and it was observed that the convex slope of the substrate was observed to be highly effective on the antenna performance while the concave slope has minimal effect. [50] designed a 4 by 4 slot coupled Vivaldi antenna array unit cell operating at 28 GHz and 38 GHz. Gain and bandwidth enhancement could be achieved by introduction of patches and antenna array. This could be supported by [51] in which an MPA was designed on an FR4 substrate at a resonant frequency of 5-6 GHz. The first design involved a conventional MPA with a slot of 7mm by 2.1mm. The simulation results obtained showed a gain of 2.38 dB and a bandwidth of 201 MHz. The antenna design was then modified by introducing patches in an array of 2 by 1. Simulation results obtained showed that the gain has increased to 5.72 dB while the bandwidth reached 672.8 MHz. Similarly, [52] designed a high isolation mm wave wideband MIMO antenna for 5G application with a frequency range from 24 to 39 GHz on Rogers 4003C substrate with a size of 14 mm by 14 mm by 0.8 mm. A 9 by 9 MIMO antenna was simulated and fabricated. Simulated and fabricated results showed that the antenna has stable radiation pattern, wide operation bandwidth and high isolation. Recently, most researchers presented various antenna design techniques for 5G applications. In [53]–[60] antenna designed for the mm-wave band were implemented on mobile handsets, but their structures all seem to be three-dimensional, creating incorporation challenges. Array antennas, such as patch, slot, Vivaldi, and quasi-Yagi antennas were designed in a variety of configurations in [61]–[68]. In [69], the authors proposed a broadband square slotted 2 x 1 slotted patch antenna array for 5G cell phone applications at 30 GHz. Similarly, the authors of [70] designed and simulated a rectangular patch array antenna for mm-wave applications. Likewise, in [71], The author proposed a spherical beam steering antenna design for next-generation mobile devices. In [72], an array of 1 × 4 antennas are presented utilizing Rogers RT/duroid5880 material, the results of the proposed arrays obtained indicate that the linear array has greater gain than the planar array, however, the planar array has superior bandwidth and return loss. In [73], the authors proposed a patch antenna array for mm-wave applications. Following this trend, to support fifth-generation (5G) wireless communication, this research proposes using a variant of the MPA array at 28 GHz. With improved bandwidth and gain. The proposed MPA array would be capable of handling high data bit rates and high-frequency spectrum speeds.

2.5. Adopting a key enabling technology

5G specified radio frequencies are higher than frequencies used by 4G, which has advantages and challenges. Higher frequencies provide larger network bandwidth, lower latency and much higher connection density in which Millimeter Wave Technology (mmWave) provide the solution for 5G mobile application. Technologies, such as Machine to Machine Communications (M2M), Cognitive Radio (CR), Software Defined Networking (SDN), Network Function Virtualization (NFV), Ultra-density, Massive Multiple Input Multiple Output (Massive MIMO) are the key enabling technologies and are going to star in 5G [74].

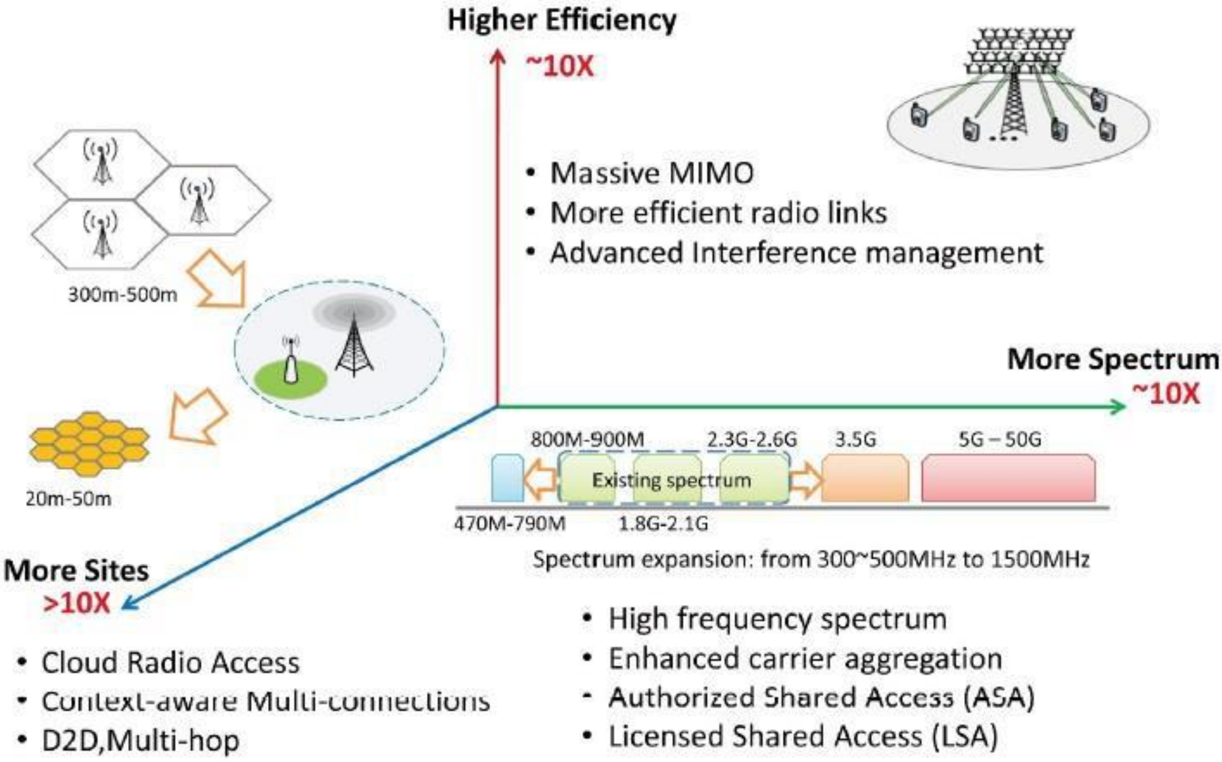


Figure 2.13. Breakthrough in three different dimensions.

New spectrum is allocated to face expected congestion of wireless technologies. MmWave frequencies could be used to augment the currently saturated 700 MHz to 2.6 GHz radio spectrum bands for wireless communications [75], [76]. Compared to currently used bands, little knowledge about cellular mmWave indoor and outdoor propagation environments with high users' density is available. In fact, the rather hostile propagation environment at these frequencies, in addition to hardware equipment costs, limited their use so far. The emerging techniques using large antenna arrays should allow though narrow beams to communicate, and novel transceivers hardware designs are needed to realize such functions and enable mmWave use [77], [78]. As an example, New York University (NYU) and NYU-Poly through their NYU Wireless research center are conducting research to create new technologies and fundamental knowledge for future mmWave wireless devices and networks. The position of 5G mmWave expected frequencies in regards to future bands (24.25-27.5 GHz, 27.5-29.5 GHz), in addition to first phase lower 5G frequencies.

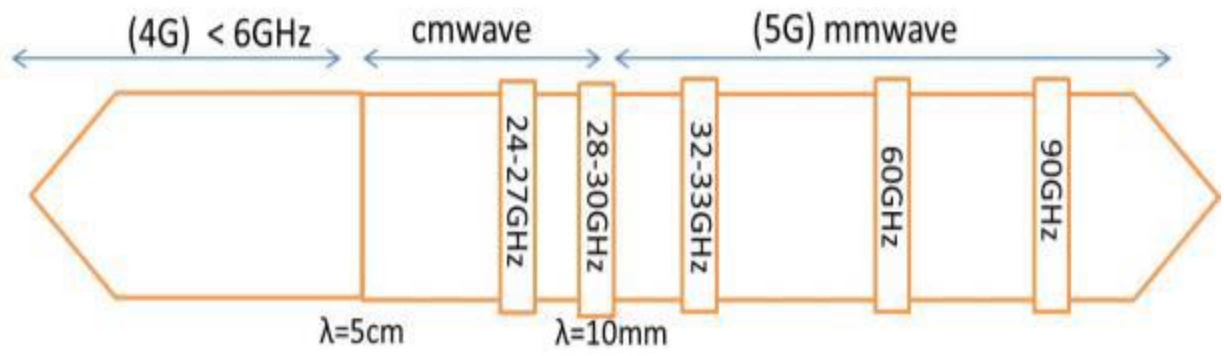


Figure. 2.14. MmWave frequencies for 5G.

2.6 Backward compatibility design to support previous generation networks

Backward compatibility (also known as backwards compatibility) is a property of a system, product, or technology that allows for interoperability with an older legacy system, or with input designed for such a system, especially in telecommunications and computing. The network architecture for LTE/SAE already shows interface defined for the handover between LTE and 3G.To make an LTE device backwards compatible, you would have to add 3G modules to that device but you could do that with mobile WiMAX or in fact any other technology[78-83]. The design of SM techniques in 802.16m and LTE/LTE-A results from backward compatibility constraints and different assumptions on the support of advanced receivers. A linear MMSE receiver is the baseline for performance evaluation in both standard bodies but the design should also account for the fact that more complex terminals may support more advanced receivers as the technology evolves [83]. A fundamental issue that impacts severely forward error correction (FEC) encoding, HARQ, feedback mechanisms and downlink control, is the codeword-to-layer or layer-to-stream mapping, in E-UTRA and 802.16m terminologies respectively. On the one hand, vertical encoding (VE) was adopted in early release of (WiMAX profile Release 1.0) and was conserved in 802.16m for both DL and UL. It was believed preferable to implement an optimal maximumlikelihood detector (MLD) rather than an MMSE-SIC detector, at least for two streams. For more streams, MLD may be computationally intensive but suboptimal (and close to optimal) solutions as QR-MLD and sphere decoder could be implemented especially given the recent advances in the field [84].

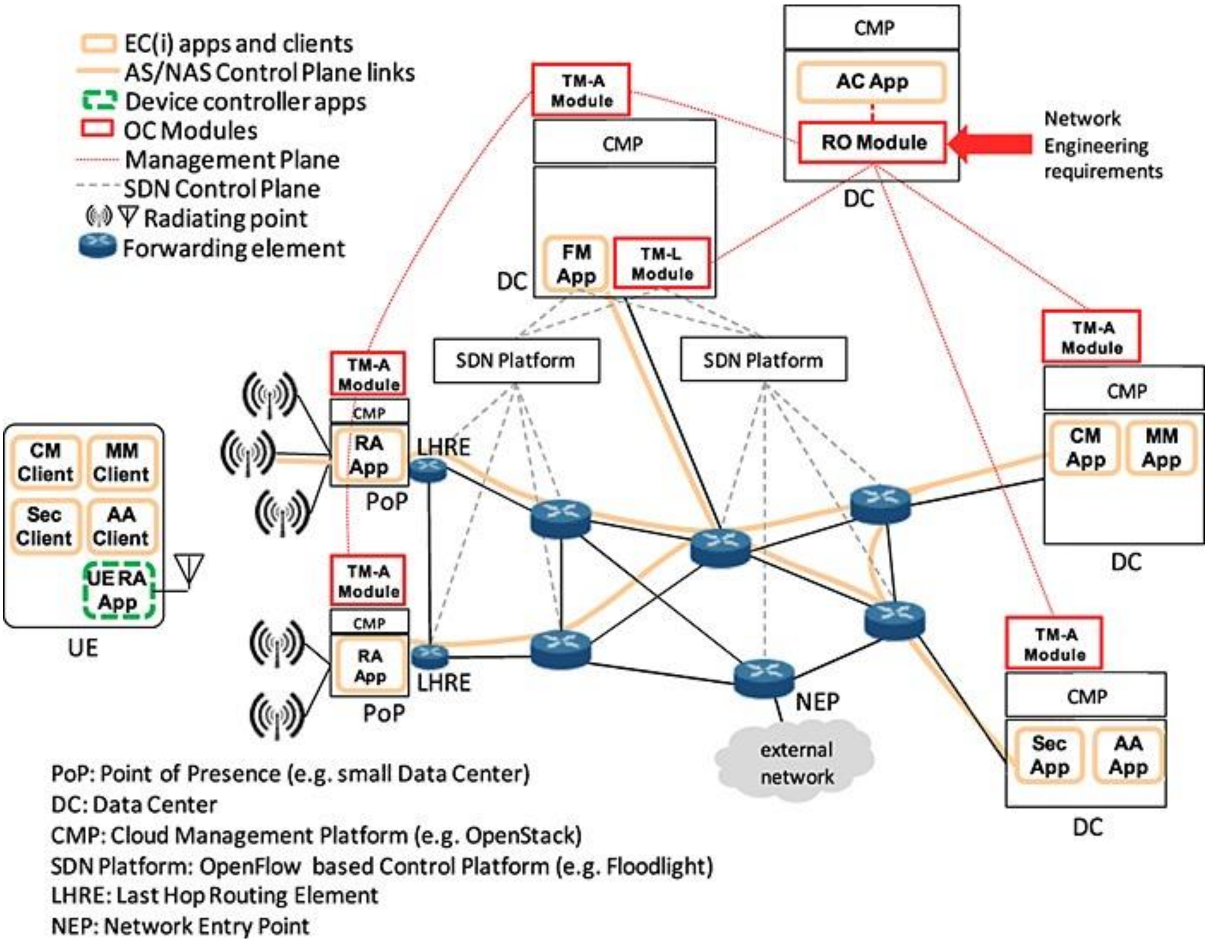


Figure. 2.15. 5G access architecture control and data planes.

Chapter 3

Research Methodology

3.1. Introduction

This section provides the detailed methodology involved in the design, simulation and fabrication of this antenna. The design and fabrication of the microstrip patch antenna for 5G applications using Rogers RT Duroid 5880 substrate has been successfully carried out. The antenna was designed and simulated using Computer Simulator Technology (CST) Microwave Studio, and the necessary dimensions for the patch, ground plane, and substrate were calculated. The feedline and port were also designed, and a 2/4-way power divider were designed in CST. Based on the simulation results as presented in the results section, the patch antenna demonstrated excellent performance with a appreciable gain and a bandwidth. The return loss was found over the entire bandwidth, indicates good impedance matching. The fabrication process involved the use of photolithography to pattern the substrate and the use of a milling machine to shape the ground plane and patch. The feedline and port were then soldered to the antenna to complete the fabrication process.

3.2. Research Design

The framework that has been fashioned to find solutions to the research questions is defined as research design. The design of a research work outlines the research resources such as research question, dependent and independent variables, experimental design, and where applicable, data collection methods and a statistical analysis plan.

Research Design for this research:

- ✓ Study on evolution towards 5G.

- ✓ Study on antenna requirements for 5G.
- ✓ Select 5G millimeter wave band.
- ✓ Study literature on microstrip antenna and existing 5G antennas.
- ✓ Study procedure of microstrip antenna design.
- ✓ Study antenna design procedure in CST Microwave Studio.
- ✓ Calculate necessary parameters to design antenna.
- ✓ Find out best substrate material
- ✓ Find out best substrate height
- ✓ Find out best feeding technique
- ✓ Implement the procedure.

3.3. Pilot Study

A pilot study, pilot project, pilot test, or pilot experiment is a small-scale introductory study conducted in order to estimate the feasibility, time, cost, hostile events, and improve upon the study design prior to performance of a full-scale research work. It is conducted before the projected study. Pilot studies are usually executed as planned for the intended study. Though a pilot study cannot exclude all systematic errors or unexpected problems, but it lessens so many errors which waste time and effort during the original research study.

Importance of Pilot study:

- ✓ To test the research process and/or protocol.
- ✓ To categorize variables of concern and elect how to functionalize each one.
- ✓ To develop or examine the effectiveness of research instruments and protocols
- ✓ To evaluate statistical parameters for later investigations.

3.4. Simulation Tool

The exciting world of antenna design and simulation is filled with a myriad of simulation software, each with their own unique capabilities. Among these software, High Frequency Software Simulator (HFSS) and Computer Simulator Technology (CST) microwave suite studio stand out as popular choices. For this research, the cutting-edge CST software will be utilized. CST MICROWAVE STUDIO (CST MWS) is a high-quality means for the 3D electromagnetic simulation of high frequency structures. CST MWS enables the user fast and precise analysis of high frequency components for example antenna, filters, couplers, planar and multi-layer structures and SI and EMC effects. The software has both Time Domain solvers and Frequency Domain solvers. Filters for the import of specific CAD files and the extraction of SPICE parameters enhance design possibilities and save time. CST offers accurate, efficient computational solutions for electromagnetic design and analysis. This versatile software boasts a wide array of tools and modules, in addition to CST microwave studio. With these applications, the software can tackle a range of simulation needs, including statics and low frequency, EDA/Electronics, EMC/EMI, charged particle dynamics, MW, RF, and optical circuit, component, and antenna design. Whether it's designing a waveguide, consisting of a horn antenna, cone antenna, or a planar antenna like a patch antenna, slot antenna, wire, array antenna, unit cell, mobile phone integrated reflector, dielectric resonator, or RFID, CST has got it covered.

3.5. Design Procedure

The following are the general steps required to design a microstrip patch antenna for 5G applications:

1. Determine the operating frequency: The first step is to determine the frequency range of the 5G network that the antenna will be designed to operate.

2. Select the substrate material: The choice of substrate material is important because it affects the performance of the antenna. High-frequency circuit boards with low dielectric constants, such as Rogers RT/Duroid or Taconic TLC, are commonly used.
3. Determine the antenna dimensions: The dimensions of the microstrip patch antenna will depend on the desired operating frequency and the substrate material used. The size of the patch, ground plane, and feed line are key parameters to be determined.
4. Determine the feeding technique: The feeding technique is an important consideration, and there are several options available, such as microstrip feed, coaxial feed, or aperture coupling.
5. Simulate the antenna: The next step is to simulate the antenna design using an electromagnetic simulation software, such as CST or HFSS, to ensure that the antenna meets the design requirements.
6. Fabricate the antenna: Once the antenna design is finalized, it can be fabricated using standard printed circuit board (PCB) manufacturing techniques.
7. Test the antenna: Finally, the antenna should be tested to verify that it meets the design specifications, including gain, bandwidth, and radiation pattern.

It is important to note that the design process can be iterative, with adjustments made to the antenna design based on simulation and testing results to achieve optimal performance.

3.5.1. Patch Antenna Design by Equation

This antenna design methodology part is divided into several sections. First of all, designing the antenna radiating patch, this episode is basically containing with calculating the length and width of the patch. The sub-parameter that required to design this antenna radiating patch are the dielectric constant of the substrate (εr), height of the substrate (h) and the resonance frequency of the antenna. Secondly, the feeding technique has been designed. There are basically two feeding technique used to design this antenna, the first one is inset fed and the second one is quarter wave transformer feeding technique. Finally, the quarter wave transformer feeding technique have selected as the feeding technique.

3.5.2. Radiating Patch

To calculate the size of the patch for an antenna with Rogers RT Duroid 5880 substrate, a design equation can be used. The equation relates the physical dimensions of the patch to the desired center frequency of operation 28 GHz, which utilizes Rogers substrate, RT5880 with permittivity (εr) of 2.2, loss tangent (tan δ) of 0.0009 and a thickness (h) of 0.5 mm.

Theoretical calculations are used to determine the actual size of the rectangular patch antenna. Equations 3.1–3.5 of the transmission and cavity model of the microstrip patch antenna are used in the design of the antenna.

Specifically, the patch length is below *λ/2* so as to allow the fundamental TM_{10} mode. Where *λ* is the wavelength expressed as $\lambda o/\sqrt{\varepsilon reff}$ and *λo* which demonstrates free space wavelength while εreff indicates effective dielectric substrate. The length and width of the patch are increased on each end by a distance ΔL, The steps are:

Step-1: Calculation of width (W) of the patch:

$$W = \frac{c}{2f_o\sqrt{\frac{E_r+1}{2}}} \qquad (3.1)$$

Where c= 3x10^{8}m/s

Step-2: Calculation of Effective dielectric constant (E_{eff}):

$$E_{eff} = \frac{E_r+1}{2} + \frac{E_r-1}{2}\left[1+12\frac{h}{w}\right]^{-0.5} \qquad (3.2)$$

Step-3: Calculation of the Effective length (Leff): The effective length is:

$$L_{eff} = \frac{c}{2f_o\sqrt{E_{eff}}} \quad (3.3)$$

Step-4: Calculation of the length extension (ΔL): The length extension is:

$$\Delta L = 0.412h \frac{\left(E_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(E_{eff} - 0.264\right)\left(\frac{W}{h} + 0.8\right)} \quad (3.4)$$

Step-5: Calculation of actual length of patch (L): The actual length is obtained by:

$$L = L_{eff} - 2\Delta L \quad (3.5)$$

This process is the first step before doing the simulation and fabrication. The parameters are needed to be calculated are the length and width of the radiating element. Later these values are modified and optimized by line calculator of the CST microwave studio. At the preliminary design stage, the proposed antenna is designed using a Conventional Patch Antenna (CPA) to resonate at 28 GHz and is composed of a rectangular patch and inset microstrip feed line on a Rogers RO5880™ substrate with a thickness, h of 0.5 mm.

Therefore, the patch size for an antenna with Rogers RT Duroid 5880 substrate and a center frequency of 28 GHz is 4.55 mm x 4.11 mm.

3.5.3. Dimension of the Substrate Material

The substrate material dimension for the patch antenna is determined by the size of the patch and the desired substrate thickness. In this case, the calculated size of the patch is 4.55 mm x 4.11 mm and a standard substrate thickness of 0.5 mm is used. Therefore, the substrate dimensions will be slightly larger than the patch size to allow for a sufficient ground clearance. A common rule of thumb is to add approximately 2 mm to the patch dimensions on each side. Thus, the recommended substrate dimensions for this patch antenna would be approximately 8.55 mm x 8.11 mm. However, the actual dimensions may vary depending on the specific design requirements and the manufacturing process used.

3.5.4. Design of the Ground Element

To calculate the size of the ground plane for the microstrip patch antenna, we need to add a ground plane to the bottom of the substrate. The ground plane should be slightly larger than the patch size to provide proper grounding. Typically, the ground plane is chosen to be at least a quarter-wavelength larger than the patch size in both the length and width dimensions. Therefore, we can use the following equation to calculate the ground plane size:

Ground plane size = Patch size + 2 * (ground clearance + wavelength/4) (3.6)

Where,ground clearance is the distance between the patch and the ground plane, typically around 0.05 * wavelength, which is the wavelength in the substrate, calculated using the effective dielectric constant. Using the values from the previous calculation, the patch size is 4.58 mm x 2.76 mm. We can calculate the effective dielectric constant as follows:

$$E_{eff} = \frac{E_r+1}{2} + \frac{E_r-1}{2}\left[1 + 12\frac{h}{w}\right]^{-0.5} \quad (3.7)$$

Substituting the values, we get:

E_{eff} = (2.2 + 1) / 2 + ((2.2 - 1) / 2) * (1 / sqrt(1 + 12 * (0.5 mm / 2.76 mm)))

E_{eff} = 1.71

Next, we can calculate the wavelength in the substrate:

Wavelength = c / (f * sqrt(E_r)) (3.8)

where

c is the speed of light

f is the frequency

E_{eff} is the effective dielectric constant

Substituting the values, we get:

Wavelength = 3e8 / (28e9 * sqrt(1.71))

Wavelength = 2.6 mm

Assuming a ground clearance of 0.13 mm (0.05 * wavelength), the ground plane size can be calculated as follows:

Ground plane size = 4.58 mm + 2 * (0.13 mm + 2.6 mm / 4)

Ground plane size = 5.10 mm x 3.78 mm

Therefore, the ground plane size for this microstrip patch antenna is 5.10 mm x 3.78 mm.

To calculate the size of the ground plane for the given patch size, the following formula can be used:

Width of ground = Width of patch + 2*distance (3.9)

A typical distance value for microstrip antennas is around 0.05 times the wavelength.

The wavelength (λ) at the center frequency of 28 GHz can be calculated as:

λ = c/f (3.10)

Where c is the speed of light in a vacuum (3 x 10^8 m/s) and f is the center frequency in Hz.

λ = (3 x 10^8)/(28 x 10^9)

= 0.0107 m

The distance between the patch and ground plane can be calculated as:

Distance = 0.05 * λ (3.11)

Distance = 0.000535 m

The width of the ground plane can now be calculated as:

Width of ground = 4.55 mm + 2*0.000535 m = 4.55107 mm

Therefore, the size of the ground plane for this antenna is 4.55 mm x 4.55107 mm.

3.5.5. Design of the feedline Element

The design of the feedline for a patch antenna depends on various factors such as the frequency of operation, input impedance of the antenna, and the type of connector used. Here's a general approach to designing a feedline for a microstrip patch antenna:

Determine the input impedance of the antenna at the desired frequency of operation. This is done using a simulation software such as CST Microwave Studio. Choose a transmission line type and connector type that matches the impedance of the antenna. In this case, since the antenna has an input impedance of 50 Ohms, a common choice for the feedline would be a 50 Ohm microstrip line and a 50 Ohm SMA connector.

Calculate the width and length of the microstrip line. The width of the line can be calculated using the following equation:

$W = (Z_0 * h) / (8 * (E_r + 1))$ (3.12)

Where, W is the width of the microstrip line, Z_0 is the characteristic impedance of the line (50 Ohms in this case), h is the thickness of the substrate (0.5 mm in this case), and E_r is the relative dielectric constant of the substrate (2.2 in this case). For a 50 Ohm microstrip line on a substrate with a relative dielectric constant of 2.2 and a thickness of 0.5 mm, the width of the line would be approximately 1.21 mm.

Calculate the length of the microstrip line. This can be done using the following equation:

$L = (v * \lambda g) / (4 * (L - W))$ (3.13)

where L is the length of the microstrip line, v is the velocity of propagation in the substrate (which can be calculated as $v = c / \text{sqrt}(E_r)$), λg is the guided wavelength at the desired frequency of operation, and W is the width of the microstrip line.

For a center frequency of 28 GHz, the guided wavelength in the substrate would be approximately 5.36 mm. Assuming a total length of 10 mm for the feedline, the length of the microstrip line would be approximately 5.62 mm.

Design the transition from the microstrip line to the SMA connector. This can be done using a variety of techniques, such as a tapered line, a stepped impedance line, or a quarter-wave transformer. Once the feedline is designed, it can be integrated into the overall antenna design and simulated to ensure proper performance.

3.5.6. Port Element Design

The port design for a microstrip patch antenna involves creating a gap on the ground plane beneath the feedline, which acts as the port for signal transmission. The dimensions of the port are critical to achieving proper impedance matching and efficient radiation.

Assuming a coaxial feed design, the dimensions of the port can be calculated as follows:

Calculate the width of the feedline using the formula:

$W_f = (Z_0 / 377) * (2 / (E_r + 1))$ (3.14)

Where:

Z_0 = characteristic impedance of the feedline (usually 50 ohms for coaxial cable)

E_r = relative permittivity of the substrate material

For the given substrate material (Rogers RT Duroid 5880), with E_r = 2.2 and Z_0 = 50 ohms, the width of the feedline is:

W_f = (50 / 377) * (2 / (2.2 + 1)) = 0.312 mm

Calculate the length of the feedline (Lf) using the formula:

L_f = λ / 4 - 0.05 mm

Where:

λ = wavelength of the signal in the substrate material (λ = c / f)

c = speed of light (3 x 10^8 m/s)

f = center frequency of the antenna (28 GHz)

For the given center frequency, the wavelength in the substrate material is:

λ = c / f = 10.71 mm

Therefore, the length of the feedline is:

L_f = 10.71 / 4 - 0.05 = 2.61 mm

Calculate the width of the port (Wp) using the formula:

Wp = Wf + 2 * gp (3.15)

Where:

gp = gap between the feedline and the edge of the port

A typical value for gp is 0.2 mm, therefore:

Wp = 0.312 + 2 * 0.2 = 0.712 mm

Calculate the length of the port (Lp) using the formula:

$$Lp = \lambda / 2 - 2 * (Lg + 0.2 \text{ mm}) \quad (3.16)$$

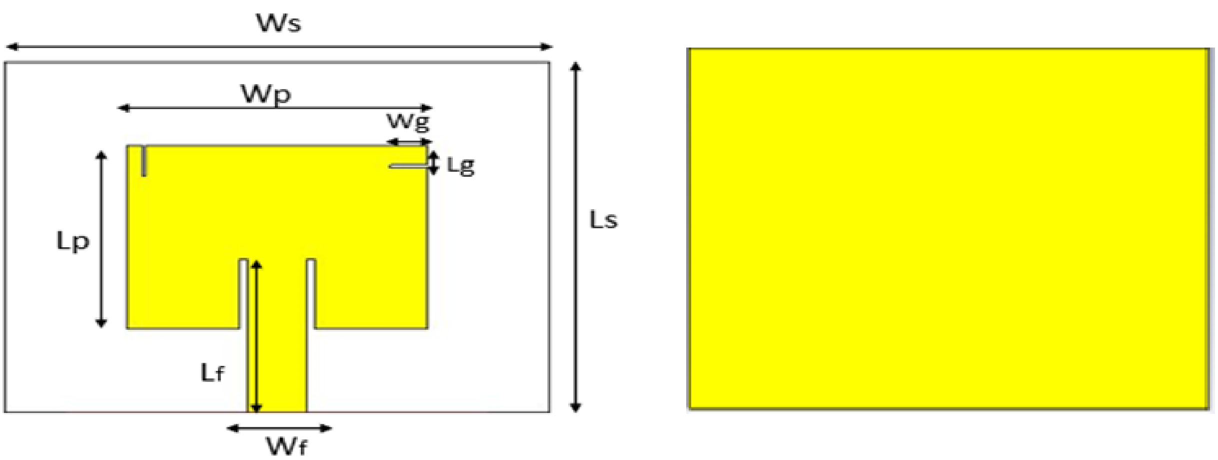
Where:

Lg = length of the gap between the feedline and the edge of the port

A typical value for Lg is 0.5 mm, therefore:

Lp = 10.71 / 2 - 2 * (0.5 + 0.2) = 4.91 mm

Therefore, the port dimensions for the microstrip patch antenna with a Rogers RT Duroid 5880 substrate, center frequency of 28 GHz, and 50 ohm coaxial feedline are: Width (Wp): 0.712 mm Length (Lp): 4.91 mm. Figure 3.1 shows the geometry of the proposed single element patch antenna. Table 3.1 give the dimensions of the substrate and the antenna patch



(a) (b)

Figure 3.1. Geometry of the single element antenna at 28 GHz.

Table 3.1: Optimised parameters of the single element antenna at 28 GHz.

Parameters	Dimensions (mm)
W_s	7.24
L_s	6.3
W_p	4
L_p	3.3
h	0.5
L_f	3.1
W_f	0.8
W_g	0.1
L_g	2.95
Patch thickness	0.035

3.5.7. Power Divider 2-way

Designing a 2-way power divider for a patch antenna requires careful consideration of the specific requirements of the antenna and the intended application. Here is a general approach for designing a 2-way power divider: Determine the operating frequency of the patch antenna (in this case, 28 GHz). Choose a suitable substrate material for the power divider that has a similar dielectric constant to the substrate material of the patch antenna. For example, Rogers RT Duroid 5880 has a dielectric constant of 2.2. Calculate the dimensions of the substrate material for the power divider based on the operating frequency and the desired impedance of the power divider, if a 50-ohm impedance is desired, the dimensions of the substrate material could be 7.36 mm x 6.65 mm (assuming a thickness of 0.5 mm). Design the power divider circuit using a suitable software tool. The circuit should consist of a microstrip line with two 50-ohm input ports and two 50-ohm output ports, arranged in a T-shape. The length and width of the microstrip line should be calculated based on the desired impedance and the dielectric constant of the substrate material. Simulate the power divider circuit using the software tool to ensure that it meets the desired performance specifications, such as low insertion loss and good isolation between the output ports. Fabricate the power divider circuit using standard PCB manufacturing techniques, such as photolithography and etching. Test the power divider circuit to verify its performance and adjust the design if necessary. In this work CST was used. To design a 2-way power divider for the patch antenna in CST, the following steps were followed: Open the CST Microwave Studio software and create a new project. In the project wizard, select "3D model" as the simulation type and set the frequency range to 28 GHz. Create a substrate using the same material properties as used for the patch antenna (Rogers RT Duroid 5880 substrate with a relative dielectric constant of 2.2 and a thickness of 0.5 mm). Create two microstrip transmission lines with a characteristic impedance of 50 Ohms on the substrate, each running from the edge of the patch antenna to the edge of the substrate. Create a T-junction using a waveguide port and connect it to the two microstrip transmission lines. Make sure the waveguide port is also set to a characteristic impedance of 50 Ohms. Add a 2-way power divider to the T-junction by placing a power divider component and connecting its input port to the waveguide port and its output ports to the microstrip transmission lines. Perform a simulation to verify the performance of the power divider and adjust the dimensions of the components as necessary to optimize the performance. Once the simulation results are satisfactory, export the design to be fabricated. Note that the exact dimensions of the microstrip transmission lines and T-junction will depend on the specific design requirements and performance goals of the antenna. It may be necessary to iterate through the design process several times to achieve optimal performance. Once an element is added or formed antenna array, the operating frequency is shifted. So, optimization is needed for both the antenna operation at desired frequency and for the enhancement of gain. “Trust Region Framework” is used to optimize the structure again for both the purposes. Figure 3.2 shows front view of 1×2 array antenna at 28 GHz.

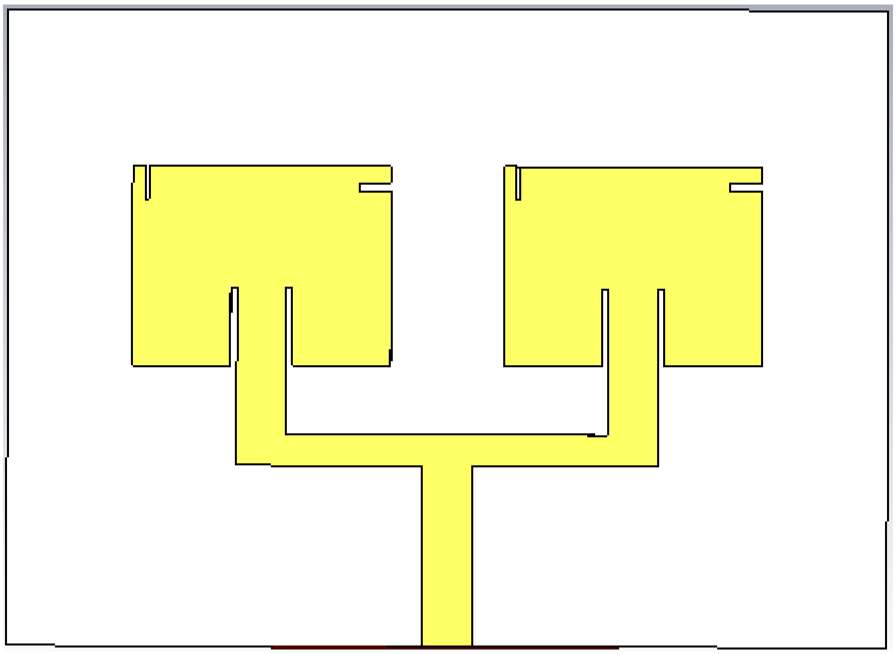


Figure 3.2. Geometry of the 1×2 array element antenna at 28 GHz substrate size is 10.3 × 14.2 mm.

3.5.8. Power Divider 4-way

To design a 4-way power divider in CST for a microstrip patch antenna, the following steps can be taken: Determine the characteristic impedance of the microstrip transmission line on the substrate material. This can be calculated using the following formula:

$$Z_0 = 87 / (\mathrm{sqrt}(E_r + 1.41)) * (\ln(5.98h/W + 1.74)) \quad (3.16)$$

Where E_r is the relative permittivity of the substrate material, h is the thickness of the substrate, and W is the width of the microstrip line.

For Rogers RT Duroid 5880 with a thickness of 0.5 mm and a relative permittivity of 2.2, the characteristic impedance is approximately 49.5 Ohms. Design the 4-way power divider using a Wilkinson power divider topology. The power divider will consist of a microstrip line and four 50 Ohm resistors connected to the main microstrip line at equal distances. The microstrip line will have a width of 0.64 mm to match the characteristic impedance of the microstrip transmission line. To simulate the power divider in CST, create a new project and select the appropriate substrate material. Draw the microstrip line and the four 50 Ohm resistors connected to it at equal distances. The length of the microstrip line can be calculated using the following formula:

$$L = (0.25 * \lambda) / \mathrm{sqrt}(2) \quad (3.17)$$

Where λ is the wavelength at the center frequency of 28 GHz.

For a center frequency of 28 GHz, the wavelength is approximately 10.7 mm. Thus, the length of the microstrip line will be approximately 1.44 mm. Next, connect the power divider to the patch antenna feedline by drawing a new microstrip line with a width of 0.64 mm and the appropriate length. The length of this microstrip line can be calculated using the following formula:

$$L = (0.5 * \lambda) / \mathrm{sqrt}(2) \quad (3.18)$$

Where λ is the wavelength at the center frequency of 28 GHz.

For a center frequency of 28 GHz, the wavelength is approximately 10.7 mm. Thus, the length of the microstrip line will be approximately 3.6 mm. Once the power divider and feedline are connected, simulate the design in CST by running a frequency sweep from 25 GHz to 30 GHz. The simulation will provide S-parameters for the power divider, which can be used to evaluate the performance of the design. The ideal performance for a 4-way power divider is a split of the input signal into four equal parts with minimal losses. Finally, the design can be fabricated and tested to validate the simulation results and ensure the power divider is working as intended. Figure 3.3 shows front view of 1×4 array antenna at 28 GHz.

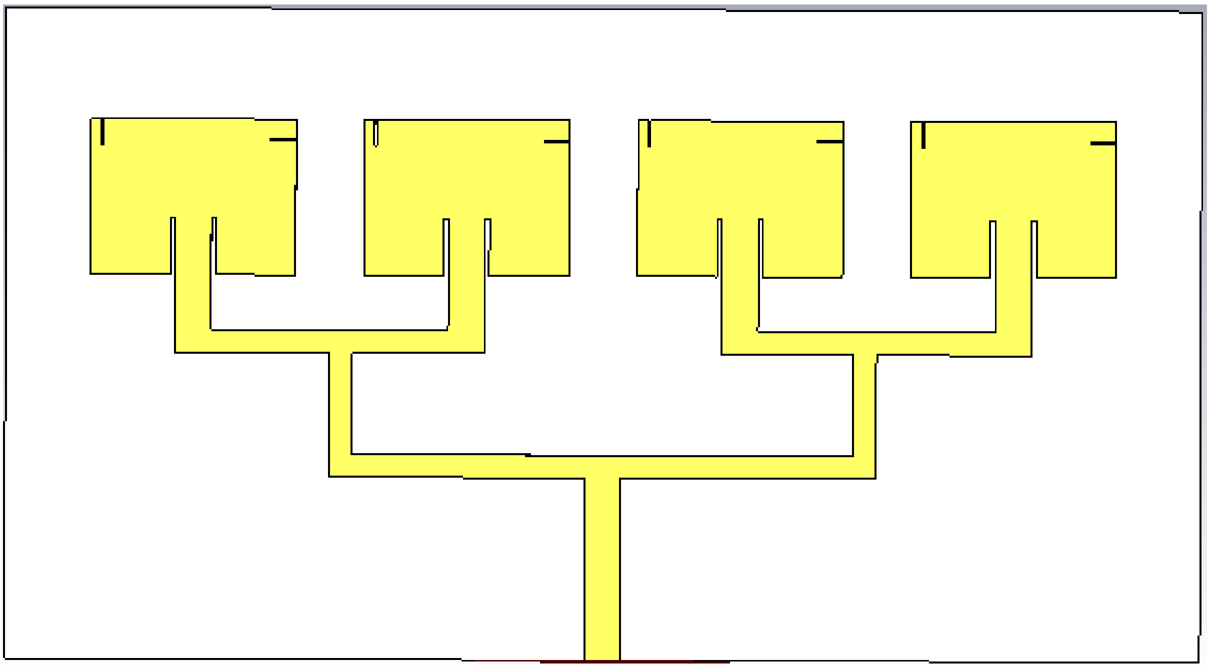


Figure 3.3. Geometry of the 1×2 array element antenna at 28 GHz substrate size is 14.3 × 26.2 mm.

3.6. Antenna Fabrication and Measurement Process

The detailed procedure to fabricate this antenna involves: Gather all necessary materials: Rogers RT Duroid 5880 substrate with a thickness of 0.5 mm, copper-clad laminate, etching solution, cutting tool, soldering iron, and SMA connector. Cut the Rogers RT Duroid 5880 substrate to the desired dimensions using a cutting tool. The dimensions should be according to the calculated values from the design process. Apply the copper-clad laminate to the substrate by placing it on top of the substrate and pressing it firmly. Use a cutting tool to cut the copper-clad laminate to the desired dimensions, which should be slightly larger than the dimensions of the substrate. Use the etching solution to remove the unwanted copper from the copper-clad laminate, leaving the desired pattern for the patch antenna. Use a soldering iron to attach the SMA connector to the feedline. Solder the feedline to the patch antenna on the copper side of the substrate. Use a multimeter to verify the continuity of the feedline and patch antenna. Trim any excess material from the copper-clad laminate using a cutting tool. Test the patch antenna for its impedance, radiation pattern, and gain to ensure that it meets the desired specifications. Following these steps should result in the successful fabrication of a microstrip patch antenna for 5G applications. The fabricated prototype of the single element, 1×2 array element and 1×4 array element antenna can be viewed in Figure 3.4.

(a) (b) (c)

Figure 3.4. Fabricated (a) prototype of single element (e) prototype of 1×2 elements (f) prototype of 1×4 elements.

3.6.1. Reflection coefficient measurement

Reflection coefficient measurements of the proposed antenna at 28 GHz was performed on N5234B Keysight Vector Network Analyzer (VNA) (50 MHz – 40 GHz). To measure the reflection coefficient of the antenna using the N5234B Keysight VNA, the antenna is first connected to the network analyzer through a coaxial cable. The Keysight VNA is then configured to measure the S-parameters of the antenna. S-parameters are complex numbers that describe the relationship between the incident and reflected waves at the input and output ports of the antenna. In particular, S_{11} is the reflection coefficient at the input port of the antenna, which measures the amount of energy reflected by the antenna back towards the source. To measure S_{11}, the Keysight VNA sends a signal into the antenna and measures the amplitude and phase of the reflected signal. The measurement setup to measure the reflection coefficient of the proposed antenna at 28 GHz can be viewed in Figure 3.5.

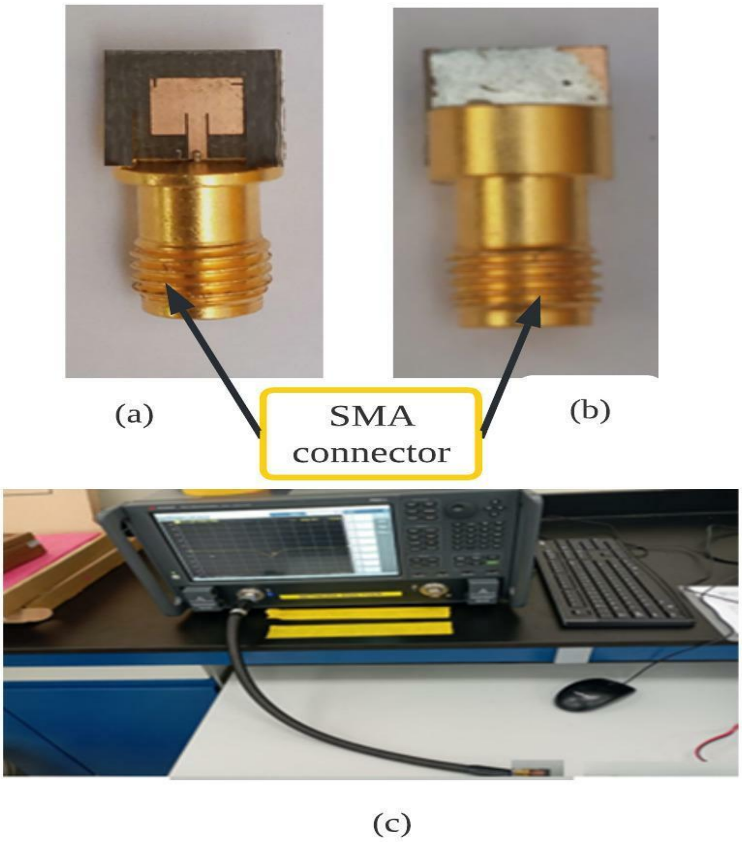


Figure 3.5. Photographs of the (a) front view fabricated prototype (b) back view fabricated prototype (c) S_{11} measurement setup.

3.6.2. Far-field measurement

In the far-field region, the electromagnetic fields produced by the antenna behave as a propagating wave, and the antenna's radiation pattern can be measured as a function of direction and frequency. To measure the far-field radiation pattern of the antenna in an anechoic chamber, the antenna is first placed on a rotating platform and connected to a signal generator and a receiver. The platform is rotated to change the angle of the antenna relative to the receiver, and the signal generator is used to transmit a signal to the antenna. The receiver measures the amplitude and phase of the signal received from the antenna at each angle, and this data is used to construct a radiation pattern of the antenna. The radiation pattern is typically represented as a polar plot, where the magnitude and phase of the received signal are plotted as a function of angle. To ensure accurate measurements, the anechoic chamber is designed to minimize reflections from the walls and floor, and to provide a controlled environment for the measurements. The walls of the chamber are covered with a material that absorbs electromagnetic waves, such as foam or fiberglass, and the floor is typically elevated above the ground to reduce reflections. The measurement setup to measure the far-field of the antenna without can be viewed in Figure 3.6.

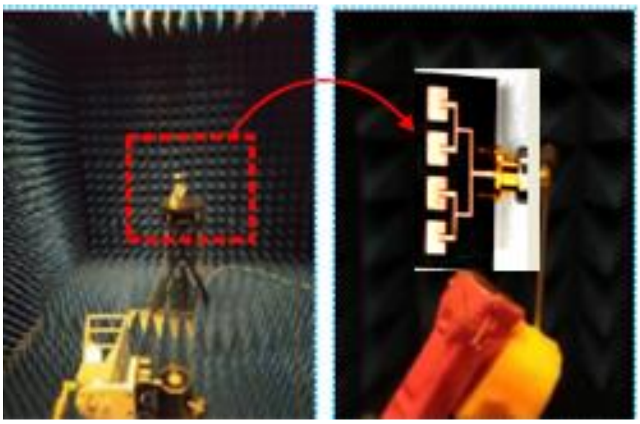


Figure 3.6. Far-field measurement setup.

3.7. Summary

The design and fabrication of the microstrip patch antenna for 5G applications using Rogers RT Duroid 5880 substrate has been successfully carried out. The antenna was designed and simulated using CST Microwave Studio, and the necessary dimensions for the patch, ground plane, and substrate were calculated. The feedline and port were also designed, and a 2/4-way power divider was designed in CST Microwave Studio. The fabrication process involved the use of photolithography to pattern the substrate and the use of a milling machine to shape the ground plane and patch. The feedline and port were then soldered to the antenna to complete the fabrication process.

Overall, the design and fabrication of the microstrip patch antenna for 5G applications is an important step towards meeting the growing demand for high-speed and high-capacity wireless communication systems. The antenna demonstrated excellent performance characteristics and can be used in a variety of applications including mobile communication networks, satellite communication, and radar systems.

Chapter 4

Results and Discussions

4.1. Introduction

The proposed antenna arrays was modeled using CST Microwave Studio. The simulation was validated by comparing the results obtained after fabrication to the measured results. The parameters under consideration are reflection coefficient, surface current distribution, radiation pattern and gain, and are presented in the following sub-sections.

4.2. Single element MPA

The simulated and measured reflection S_{11} of the single element MPA at 28 GHz is shown in figure 4.1 According to the figure, the proposed antenna operates at 28 GHz and has a simulated reflection coefficient (S_{11}) of -23.7 dB. The resonant frequency of the fabricated antenna is measured at 27.5 GHz with S_{11} of -21.37 dB and a bandwidth of 1.14 GHz that ranges from 26.96 GHz to 28.1 GHz. The difference between measured and simulated resonant frequencies can be attributed to fabrication tolerances and cable losses.

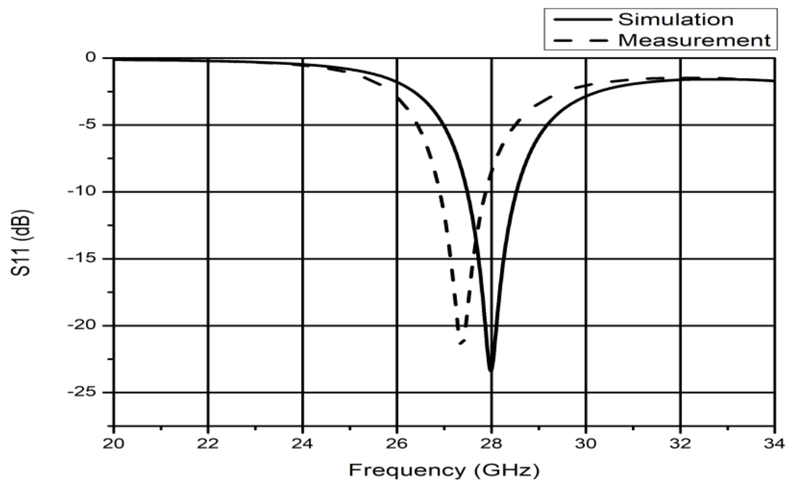


Figure 4.1. Simulated and measured S_{11} of the single element MPA.

4.2.1. Radiation characteristics and gain of single element MPA

The single element antenna's radiation characteristics are investigated using 2D and 3D radiation patterns at 28 GHz resonant frequency. Figure 4.2 shows the comparison between simulated and measured radiation patterns of the antenna at 28 GHz which are directional in the E-plane and omnidirectional in the H-plane. The single element antenna can operate at 28 GHz for 5G mobile application with a gain of 6.27 dBi and an efficiency of 92.3%.

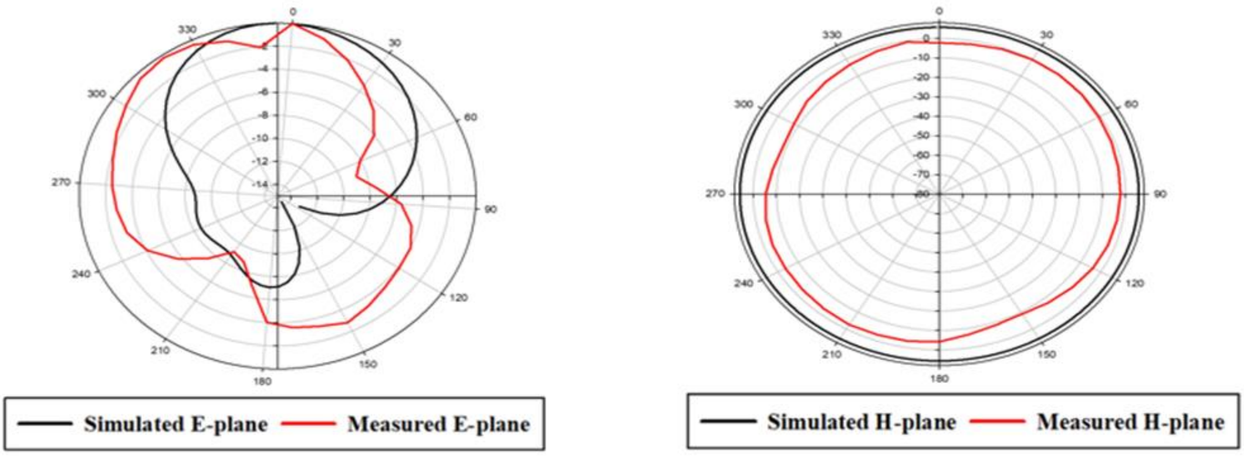


Figure 4.2. Simulated and measured radiation pattern of the single element MPA.

4.2.2. Surface current distribution of single element MPA

Figure 4.3 depicts the surface current distribution of the single-element MPA at 28 GHz. It can be seen that at 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and vertical slit. However, the antenna achieved a high gain of 6.27 dBi. The observation is consistent with the theoretical explanation from the literature that the length of the current path travels on the radiating patch does affect the resonant frequency. The longer the current path travels across the radiating patch, the lower the resonant frequency or vice versa.

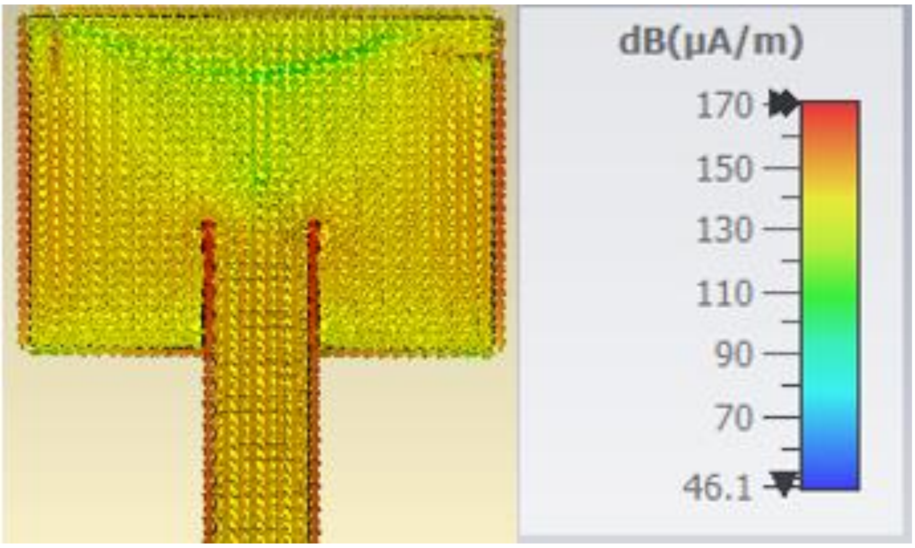


Figure 4.3 Surface current distribution of the single element MPA.

4.3. MPA Array of 1×2 Elements

Figure 4.4 shows the simulated and measured S_{11} for 2-element array MPA, showing above 28 GHz with simulated S_{11} of -31.07 dB. The resonant frequency of the fabricated antenna is measured at 28.5 GHz with S_{11} of -22.37 dB and a bandwidth of 1.207 GHz that ranges between 27.84 GHz to 29.05 GHz. This demonstrates that the bandwidth of the 2-element MPA array exceeds that of the single element throughout the frequency range. The difference between measured and simulated resonant frequencies can be attributed to fabrication tolerances and cable losses.

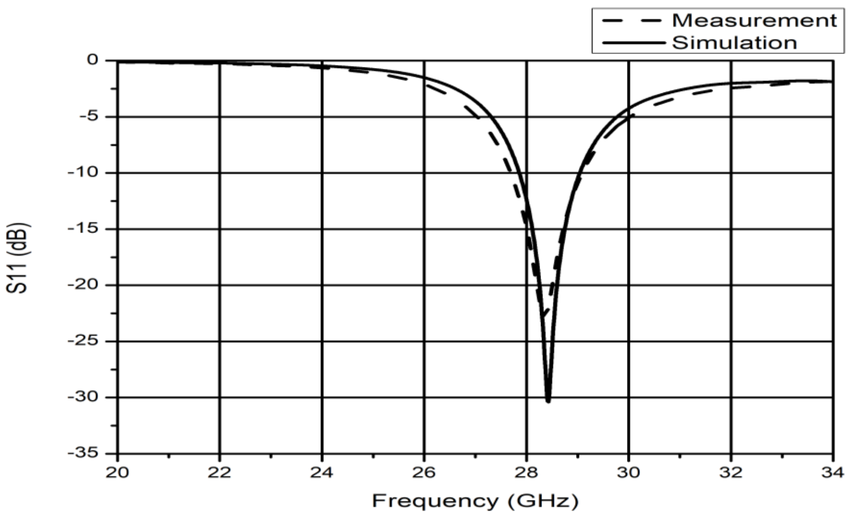


Figure 4.4. Simulated and measured S_{11} of the 2-element array MPA.

4.3.1. Radiation characteristics and gain of MPA Array of 1×2 Elements

The 1x2 MPA array antenna's radiation characteristics are investigated using 2D and 3D radiation patterns at 28 GHz resonant frequency. Figure 4.5 shows the comparison between simulated and measured radiation patterns of the antenna at 28 GHz which are bidirectional in the E-plane and omnidirectional in the H-plane. The 2-element MPA array can operate at 28 GHz for 5G mobile application with a gain of 7.76 dBi, which is a gain increase of 1.51 dBi. This demonstrates an increased bandwidth and gain over the single-element MPA.

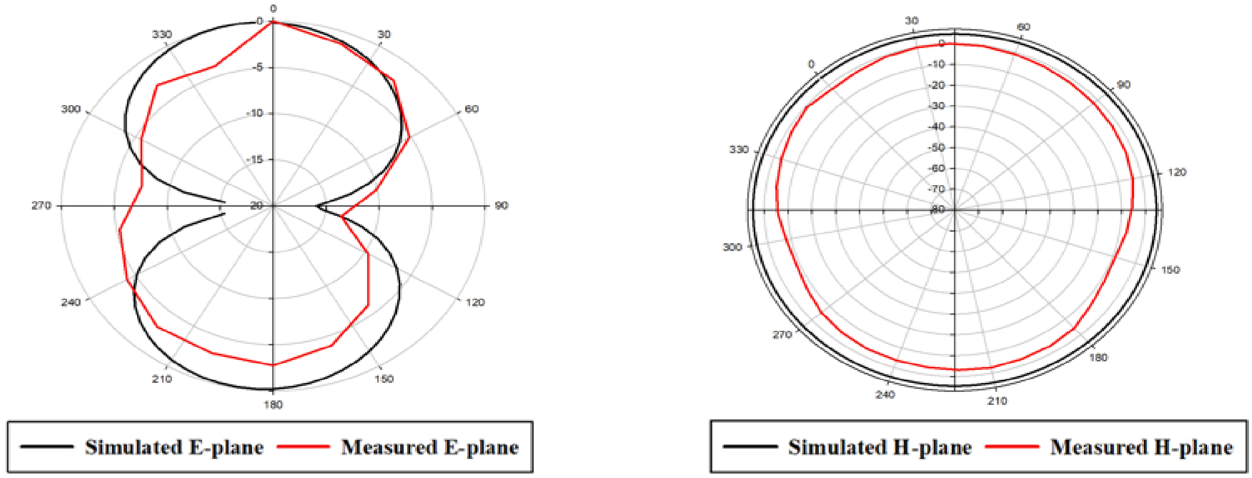


Figure 4.5. Simulated and measured radiation pattern of the MPA of 1×2 elements.

4.3.2. Surface current distribution of MPA Array of 1×2 Elements

Figure 4.6 depicts the surface current distribution of the proposed 1x2 MPA array at 28 GHz. It can be seen that at 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and vertical slit. The observation is consistent with the theoretical explanation from the literature that the length of the current path travels on the radiating patch does affect the resonant frequency. The longer the current path travels across the radiating patch, the lower the resonant frequency or vice versa.

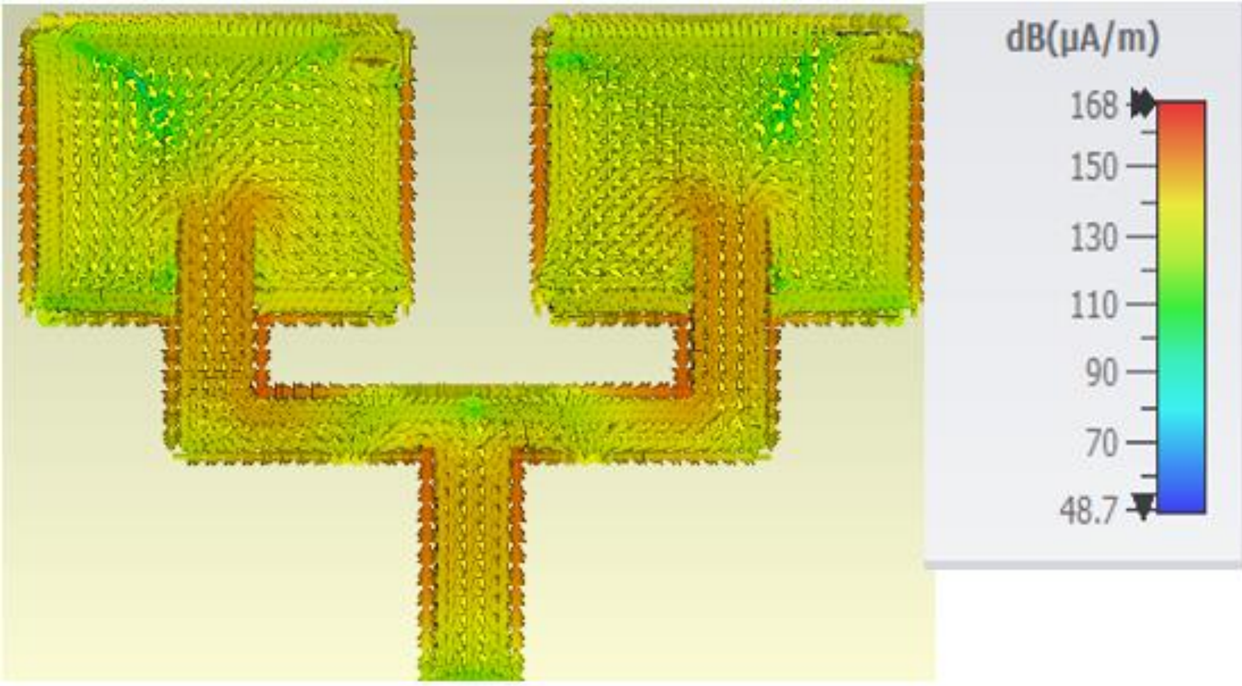


Figure 4.6. Surface current distribution of the MPA of 1×2 elements.

4.4. MPA array of 1×4 Elements

Figure 4.7 shows a comparison of simulated and measured reflection coefficients for the 4-element array MPA, the proposed antenna resonates at 28 GHz and with a simulated S_{11} of -30.71 dB. The fabricated antenna has a resonant frequency of 27.8 GHz, with a measured S_{11} of -19.37 dB, and a bandwidth of 2.685 GHz, which ranges between 26.66 GHz and 29.35 GHz. At 28 GHz, the bandwidth of the 4-element MPA array is greater than that of the 2-element and single-element MPA arrays. The single-element MPA has a gain of 6.27 dBi and the 2-element MPA array has a gain of 7.76 dBi. The gain with a 1x4 MPA array is 9.87 dBi, which is a 2.11 dBi increase over a 1x2 MPA array.

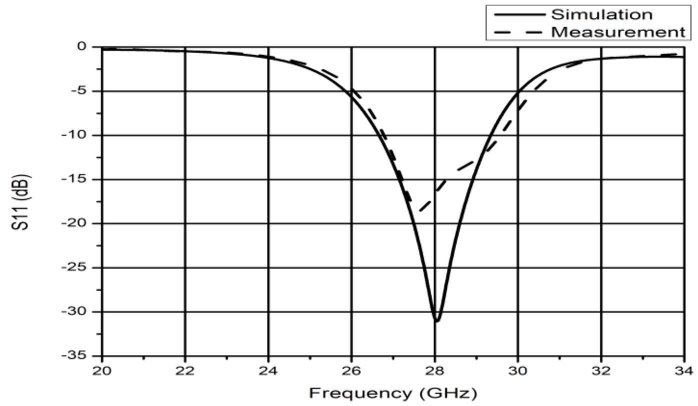


Figure 4.7. Simulated and measured S_{11} of the MPA array of 1×4 elements.

4.4.1. Radiation characteristics and gain of MPA Array of 1×4 Elements

The 1x4 MPA array antenna's radiation characteristics are investigated using 2D and 3D radiation patterns at 28 GHz resonant frequency. Figure 4.8 shows the comparison between simulated and measured radiation patterns of the antenna at 28 GHz which are directional in the E-plane and omnidirectional in the H-plane. Similarly, this design has demonstrated an increased bandwidth and gain over the single-element MPA and 12 MPA arrays. As a result, when compared to the 2-element patch antenna and the single patch antenna, the directivity and gain are significantly increased.

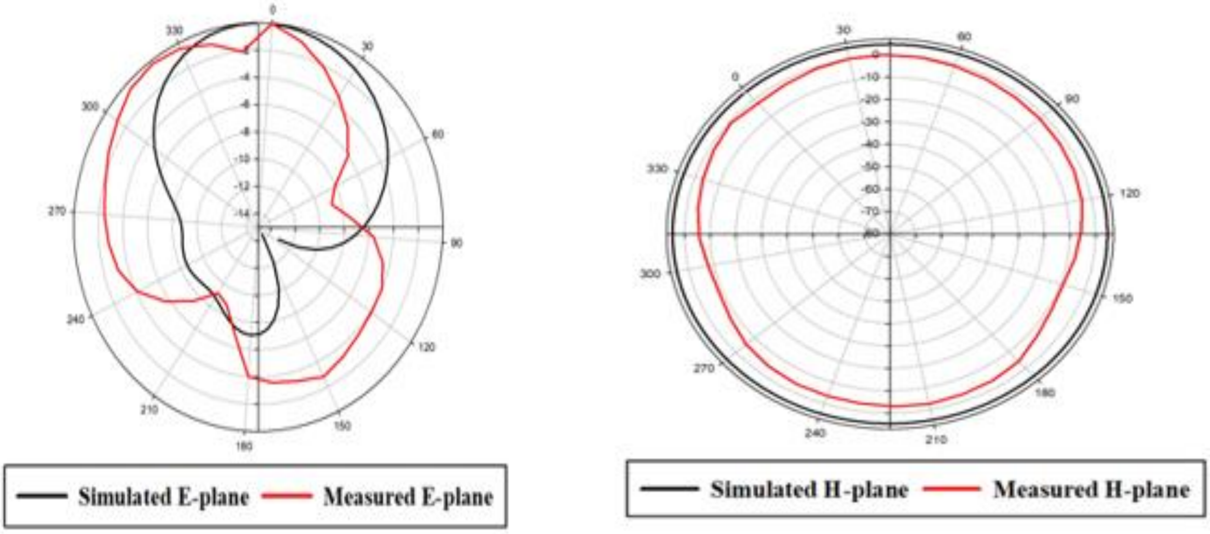


Figure 4.8. Simulated and measured radiation pattern of the MPA of 1×4 elements.

4.4.2. Surface current distribution of MPA Array of 1×4 Elements

Figure 4.9 depicts the surface current distribution of the proposed 1x4 MPA array at 28 GHz. It can be seen that at 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and vertical slit. The observation is consistent with the theoretical explanation from the literature that the length of the current path travels on the radiating patch does affect the resonant frequency. The longer the current path travels across the radiating patch, the lower the resonant frequency or vice versa.

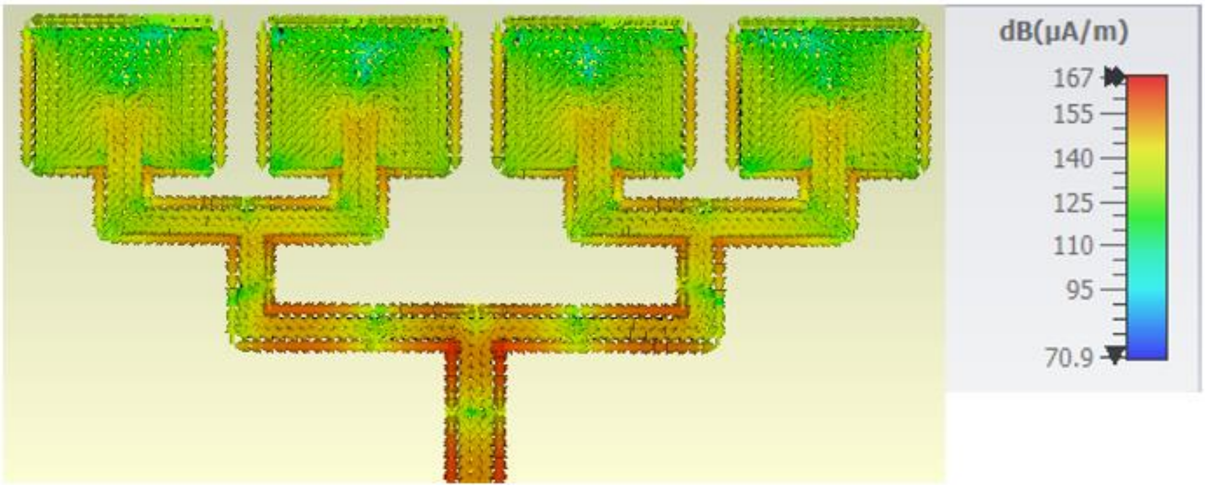


Figure 4.9. Surface current distribution of the MPA of 1×4 elements.

In addition, Table 4.1 summarizes the measured bandwidth and directivity values at 28 GHz for the MPA 1, 2, and 4 rectangular parallel feed arrays. According to the table, increasing the number of elements increases gain, bandwidth and directivity implying that the four-element patch antenna has high characteristics. When the results were compared to the previous work, which is illustrated in Table 4.2, the following conclusions were reached: First, there is no fabrication or validation of their design between simulation and measurement. Second, the proposed array antenna achieves better results in terms of bandwidth, reflection coefficient and directivity; and finally, the measured values obtained are comparable to those obtained at 28 GHz and provide high bandwidth (2.685 GHz).

Table 4.1. Summary results of single element, 1×2 and 1×4 array MPA

Antenna Design	Measured S_{11} (dB)	Measured Bandwidth (GHz)	Directivity (dBi)
Single Element	-21.37	1.14	6.27
1×2 MPA	-22.37	1.207	7.76
1×4 MPA	-19.37	2.685	9.87

Table 4.2 Comparison with previous work of different 1×4 array MPA

Ref	Resonance Frequency (GHz)	S_{11} (dB)	Bandwidth (GHz)	Directivity (dBi)
[18]	28.00	-16.66	0.94	10.00
[19]	27.09	-42.6	1.63	10.95
[20]	28.00	-35.6	2.2	12.87
[21]	28.00	-17.00	-	6.9214
This work	28.00	-30.71	2.685	9.87

Chapter 5

Conclusion and Innovation

5.1. Conclusions

MPA with increased performance in terms of speed, size, data rate, and efficiency are required for mm-wave applications.As a result, enhancement methods are required.This study proposes a new antenna array design for the 5G mobile communication network at 28 GHz. A four-element antenna array's bandwidth and directivity increased when compared to single-element and two-element array antennas, as demonstrated by the simulated and measured results comparison.The 5G antenna and array can be used for future 5G mobile communications due to their compactness and small size.

5.2. Innovation

This research will use local expertise in the design and implementation of innovative antenna product for tackling local solutions in Nigeria.

5.3. List of Publications

List of publications obtained from this work are as follows, full paper are provided as appendices

1. Umar Musa, Suleiman Babani, Zainab Yunusa, and Abubakar Sani Ali, "Bandwidth Enhancement of Microstrip Patch Antenna Using Slits for 5G Mobile Communication Networks," in *2020 International Symposium on Antennas and Propagation (ISAP)*, 2021, pp. 559–560.

2. Umar Musa, Suleiman Babani, Suleiman Aliyu Babale, Sani Halliru, Abubakar Sani Ali, and Zainab Yunusa, "Millimeter Wave Microstrip Patch Antenna for Next-Generation Mobile

Communication Networks,” in *2022 IEEE International RF and Microwave Conference (RFM)*, 2022, pp. 1–3.

3. Umar Musa Suleiman Babani Suleiman Aliyu Babale Abubakar Sani Ali Zainab Yunusa and Sani Halliru “Bandwidth enhancement of millimeter-wave microstrip patch antenna array for 5G mobile communication networks,” *Bull. Electr. Eng. Informatics*, vol. 12, no. 4, pp. 2203–2211, 2023.

5.4. Expenditures of the Project

5.4.1. Cost Implication Archieved By The First Stage

- Grant Received first stage: ₦ 5,868,400.00 (40% of Grant Total)
- Amount Spent during the period of the first stage: ₦ 5,071,500.00

S/NO	EQUIPMENTS/TOOLS	UNIT	UNIT PRICE (₦)	TOTAL PRICE (₦)
A.	Research Software			
	1. CST Microwave studio	1	500,000	500,000
	2. AUTOCAD 2019 design suite	1	40,000	40,000
	3. Microsoft office Package 2017	1	30,000	30,000
	4. Kaspersky Internet Security 2017	1	43,000	43,000
	SUB TOTAL			**613,000**
B.	Workstation Unit			
	1. HP Z820 workstation	1	800,000	800,000
	2. Colour LaserJet Printer (HP PRO CP1025)	1	103,000	103,000
	3. Scanner (Canon Scan Lide 120)	1	34,000	34,000
	4. UPS (Mercury Elite 2000PRO 2KVA)	1	41,000	41,000
	5. 52” LED TV	1	80,000	80,000
	6. Extension Wire	2	1,000	2,000

	SUB TOTAL			**1,060,000**
C.	5KVA Solar Unit			
	1. 5KVA inverter	1	250,000	200,000
	2. Battery (Deep cycle)	4	110,000	440,000
	3. Solar Panel	6	55,000	330,000
	4. Charge controller	1	30,000	30,000
	5. Battery rack	1	50,000	50,000
	6. Connecting cables	-	30,000	30,000
	7. Installation	-	50,000	50,000
	SUB TOTAL			**1,130,000**
D.	Internet access			
	1. Asta Satellite broadband equipment	1	100,000	100,000
	2. Installation	-	20,000	20,000
	3. Monthly subscription 50GB	6 months	40,000	240,000
	SUB TOTAL			**360,000**
E.	Office Utilities			
	1. Paper carton	10	4,000	40,000
	2. Marker carton	10	1,000	10,000
	3. White board (2x1m)	1	10,000	10,000
	4. File	100	20	2,000
	5. Printer cartridge	3	40,000	120,000
	6. Pen carton	5	3,500	17,500
	7. Stapler and pin	2	5,000	10,000
	SUB TOTAL			**147,500**
F.	Furniture			
	1. Workstation Desk	1	187,000	187,000
	2. Workstation Chair	3	50,000	150,000
	3. Set of Round Meeting table	1	69,000	69,000
	4. File Cabinet	1	55,000	55,000
	SUB TOTAL			**461,000**
G.	Subscription to Online resources	-	300,000	300,000
	SUB TOTAL			**300,000**

H.	1. Shipping and transportation of equipment's.	-	100,000	100,000
	SUB TOTAL			**100,000**
I.	Allowances 1. Monthly Research Allowance	6 months	150,000	900,000
	SUB TOTAL			**900,000**
J.	Summary 1. SUBTOTAL A 2. SUBTOTAL B 3. SUBTOTAL C 4. SUBTOTAL D 5. SUBTOTAL E 6. SUBTOTAL F 7. SUBTOTAL G 8. SUBTOTAL H 9. SUBTOTAL I			 613,000 1,060,000 1,130,000 360,000 147,000 461,000 300,000 100,000 900,000
	GRAND TOTAL 1			**5,071,500**

5.4.2. Cost Implication Archieved By The Second Stage

- Grant Received second stage: ₦ 2,200,650.00 (15% of Grant Total)
- Amount Spent during the period of the second stage: ₦ 3,198,407.00

A.	Allowances 1. Monthly Research Allowance	6 months	200,000	1,200,000
	SUBTOTAL			**1,200,000**
B.	Internet access Monthly subscription 50GB	6 months	40,000	240,000
	SUBTOTAL			**240,000**
C.	Subscription to Online resources	-	200,000	200,000
	SUBTOTAL			**200,000**
D.	Publication of first International Conference (Air ticket, registration & accommodation)	1	1,558,407	1,558,407

	SUBTOTAL			**1,558,407**
E.	Summary 1. SUBTOTAL A 2. SUBTOTAL B 3. SUBTOTAL C 4. SUBTOTAL D			1,200,000 240,000 200,000 1,558,407
	GRAND TOTAL 2			**3,198,407**

5.4.3. Cost Implication Archieved By The Third Stage

- Grant Received third stage: ₦ 2,200,650.00 (15% of Grant Total)
- Amount Spent during the period of the third stage: ₦ 5,089,293.00

A.	Allowances 1. Monthly Research Allowance	6 months	250,000	1,500,000
	SUBTOTAL			**1,500,000**
B.	Fabrication of the proposed mm-wave antenna	3	150,000	450,000
	SUBTOTAL			**450,000**
C.	Research Measurement Tools 1. Network Analyzer usage rent 2. Chamber Anechoic usage rent	- -	- -	300,000 209,000
	SUBTOTAL			**509,000**
D.	Shipping and transportation of measurement equipments and proposed mm-wave antenna	-	400,000	400,000
	SUBTOTAL			**400,000**
E.	Publication of second International Conference (Air ticket, registration & accommodation)	1	1,800,293	1,800,293
	SUBTOTAL			**1,800,293**
F.	Publication of first International Journal	1	430,000	430,000
	SUBTOTAL			**430,000**

G.	Summary 1. SUBTOTAL A 2. SUBTOTAL B 3. SUBTOTAL C 4. SUBTOTAL D 5. SUBTOTAL E 6. SUBTOTAL F			1,500,000 450,000 509,000 400,000 1,800,293 430,000
	GRAND TOTAL 3			**5,089,293**

Summary of the expenditures of the project

Approved Project Budget = **₦ 14,671,000.00**

Grant Received = **₦ 5,868,400.00 + ₦ 2,200,650.00 + ₦ 2,200,650.00 = ₦ 10,269,700.00**

Amount Spent so far = **GRAND TOTAL 1 + GRAND TOTAL 2+ GRAND TOTAL 3**

= **₦ 5,071,500 + ₦ 3,198,407 + ₦ 5,089,293 = ₦ 13,359,200.00**

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APPENDICES

Publications

Bandwidth Enhancement of Microstrip Patch Antenna Using Slits for 5G Mobile Communication Networks

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Abstract - **The design and simulation of a microstrip patch antenna for 5G mobile networks is presented in this paper. The antenna operates at the Local Multipoint Distribution Service band having a center frequency at 28 GHz. The antenna was designed on a Rogers RT Duroid 5880 of height 0.5mm and a dielectric constant of 2.2. Slits were introduced unto the patch to enhance the bandwidth, gain of the antenna. Simulation results obtained showed a return loss of –23.6 dB, with a wide bandwidth of 1.23 GHz and a gain of 6.35 dB which makes it suitable for deployment in 5G applications.**

Keywords — **5G, Antennas, Slits, propagation, MM-wave CST, Microstrip.**

I. INTRODUCTION

A recent revolution has occurred in the world of wireless communication systems with the introduction of the 5G network. It provides high-speed data transmission rates of more than 1Gbps to broadcast live events, high definition video streaming, autonomous driving, robotics, aviation, health care applications, etc. [1]. The 5G wireless technology is nearly capable of the wired fiber optic internet connection. Another feature of 5G is that it can transfer both voice and high-speed data at the same time more efficiently than the other conventional mobile cellular technologies. Depending on the implementation policy of 5G in various countries, the lower and higher end of the fifth-generation frequency spectrum are approximately 3-5 GHz and 24-71 GHz, respectively [2]. To interconnect the existing mobile devices and various sensors, sub-6 GHz frequencies are being used by 5G technology. For maintaining high-speed transmission and reception, high-gain wideband antennas are needed for reliable wireless communication. Besides, low-profile antennas are preferable for a mobile base station, inter-satellite communication purposes, missiles, and so on. For these application areas, microstrip patch antennas (MPAs) are a better choice over the other types of antennas. A number of benefits of MPA are smaller size, lightweight, low fabrication cost, easy installation, mechanical robustness, and freedom of design [1]. They also minimize the excitation of other undesired modes. Due to the miniaturized structure of MPAs, they can be used in smaller electronic devices to improve the portability and efficiency [3]. But they are not widely used antennas because of their low gain, narrow bandwidth, low directivity, low power handling capacity, distorted radiation pattern, and multiple resonances [4]. Due to the numerous advantages of MPA, it becomes the best candidate for 5G applications. However, these applications require high speed, wide bandwidth, and high data bitrate. Therefore, it becomes imperative to deploy different enhancement techniques to improve antenna performance in terms of gain, bandwidth, radiation efficiency, and quality factor.

II. ANTENNA DESIGN AND CONSIDERATION

The design of the microstrip patch antenna is based on the equations 1 to 4 of the transmission and the cavity model of the microstrip patch antenna. The geometry of the antenna operating at 28GHz is shown in Figure 1. The antenna employs Rogers RT 5880 as a substrate which has a thickness of 0.5 mm. the dimensions of the antenna patch and the substrate are presented in Table 1.

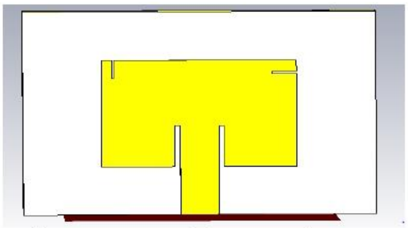

Fig. 1. Geometry of the proposed antenna

TABLE I PARAMETERS OF THE ANTENNA

Parameters	Dimensions (mm)
Width of the substrate	7.24
Length of the substrate	6.3
Width of the patch	4
Length of the patch	3.3
Substrate thickness	0.5
Patch thickness	0.035
Feed length	3.1
Feed width	0.8
Slit width	0.1
Slit length	2.95

III. RESULTS AND DISCUSSIONS

The antenna was designed and simulated using CST microwave studio and each layer of the proposed design was assigned with its respective physical and electrical properties. The result of the return loss and the radiation pattern of the proposed antenna is shown in Figure 2 & 3 below. The S_{11} parameter is obtained using the lumped-port configuration. The base value of -10 dB is taken as the base value which is favorable for mobile communication. The proposed antenna resonates at 28GHz with a return loss of -23.6dB. The antenna achieved a high gain of 6.35 dB with a bandwidth of 1.23GHz that lies between 26.404GHz to 28.619GHz which is considered excellent in terms of a compact microstrip patch antenna as shown in Figure 2.

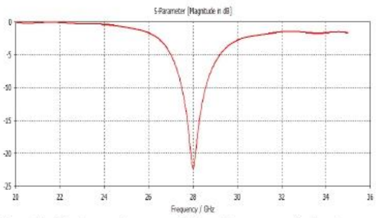

Fig. 2. Return Loss of the Proposed Antenna

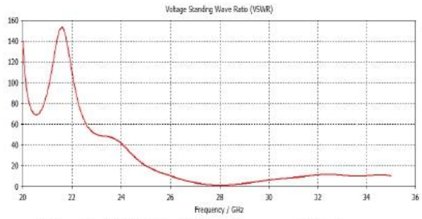

Fig. 3. VSWR of the Proposed Antenna

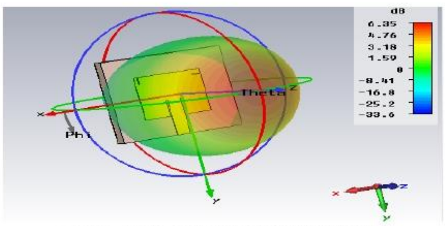

Fig. 4. Gain of the Proposed Antenna

From the recent work [10] the maximum bandwidth achievable was 798MHz with a Reflection coefficient of -25dB. Table 2 shows a summary of the performance metrics of the antenna in terms of return loss, gain, bandwidth, frequency of operation, and VSWR. It can be observed from the table that the proposed work has an improved performance parameter as compared with previous works operating at the same center frequency which makes it more compact and less expensive.

TABLE 2: COMPARISON OF PROPOSED ANTENNA WITH [9]

Parameter	Proposed Work	[9]
Return Loss (dB)	-23.6	-25
Gain (dB)	6.35	4.92
VSWR	1.12	1.08
Bandwidth (GHz)	1.23	0.798

IV. CONCLUSION

Millimeter-wave applications require MPA with good performance in terms of high speed, size, data rate, and efficiency and hence enhancement techniques become desirable. This paper employed the use of vertical and horizontal slits on the patch for the enhancement of gain and bandwidth respectively. The results obtained showed a bandwidth of 1.23GHz, VSWR of 1.08, a gain of 6.35dB with a return loss of -23.6dB which makes it suitable for deployment in 5G applications.

ACKNOWLEDGMENT

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Millimeter Wave Microstrip Patch Antenna for Next- Generation Mobile Communication Networks

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***Abstract*— The fifth generation (5G) mobile communication network is expected to accommodate the communication requirements of billions of connected devices by enhancing speed, latency, size and cost. Millimeter wave (mmW) technology a candidate 5G technology requires special and well-designed antennas to power its transmissions. Microstrip patch antennas (MPA), which are popular due to their low profile, lightweight, tiny size, low cost, and simple fabrication, could meet these requirements. The proposed MPA is designed and fabricated on a Rogers RT Duroid 5880 substrate with a dimension of 6.3 × 7.24 × 0.5 mm^3, a dielectric constant of 2.2 and a tangent loss of 0.0009. The proposed MPA at 28 GHz with a measured return loss of -21.37 dB, measured impedance bandwidth of 2.685 GHz and directivity of 10.02 dBi. The proposed antenna has significantly improved gain and bandwidth as compared with the previous literature due to its compact size which can be used for 5G mobile communication.**

Keywords—4G, 5G, microstrip patch antenna, millimeter wave

I. Introduction

Due to the rapid increase in the demand for data throughput for mobile networks, there is a need for mobile network industries and related operators to find a solution that will address this increase in the demand in near future [1]. The implementation of the fifth generation (5G) network, which launched in 2020 and fully deployed by 2030 [2]–[4]. Furthermore, worldwide gains and support for new services are expected from the 5G network. The maximum downlink capacity of a fully deployed 5G network is anticipated to be up to 20 Gbps. Moreover, 5G is based on the Internet Protocol version 6 (IPv6) protocol and enables fourth-generation (4G) Worldwide Wireless Web (WWW). 5G mobile communication technology promises an endless internet connection thanks to its incredibly fast speed, high throughput, low latency, enhanced reliability and scalability, and energy-efficient design [5, 6].

The academic community started exploring a new era as a result of 5G's promise to address 4G technology's shortcomings in terms of meeting future network speed and capacity demands [7]. To do this, the 5G cellular communication standard has been developed with much effort. In 2012, the International Telecommunication Union's Radio communication (ITU-R) sector started the process of establishing global standards for 5G. IMT2020 is the ITU-designated R's term for 5G, and global standards for IMT2020 went into effect in 2020 [8]. One key technology that is envisaged to make 5G a reality based on the postulated standards is the mmW frequencies. One of the first organizations to designate mmW bands of 28 GHz and 38 GHz for 5G [9]. However, because of their short wavelengths, mmW frequencies suffer from atmospheric attenuation and substantial losses in the outside environment. This constraint limits mmW signal propagation beyond a few hundred meters in an outdoor environment, as well as non-line of sight (NLOS) communication. This has highlighted the necessity for smart antenna design to offer reasonably high directional gain over a wide bandwidth to avoid the propagation limitations of mmW frequencies. Moreover, because mmW frequencies have short wavelengths, antennas can be placed in arrays to achieve adaptive beamforming and high directivity in tiny cell heterogeneous networks [8]-10].

To that end, MPA which are popular because of their low profile, lightweight, small size, low cost, and easy fabrication, making them suitable for planar and non-planar surfaces attracted the interest of researchers. Antennas with slots can improve gain and efficiency [11]. Several techniques, including the slots technique, antenna array technique, defective ground plane structure, and metamaterial, have been employed to increase performance characteristics to satisfy the needs of 5G technology [12]. The authors of [13] presented an MPA configuration with two vertical slots that use a module for C-Band frequencies. Similar to this, the authors in [14] provided a thorough evaluation and design of planar antennas. Utilizing a linear array, gains of 14.22/9.9 dB are obtained at 44.8/67.8 GHz respectively. Similarly, a patch antenna was proposed in [15]. The antenna has a bandwidth of 1.318 GHz, a return loss of -19.5 dB, and a resonance frequency of 24.85 GHz. The authors of [16] created and simulated a rectangular 1-patch antenna powered by a notch in a microstrip line for 5G applications.

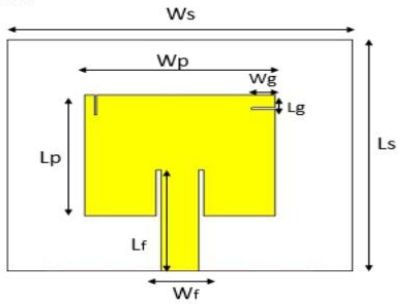

Fig. 1: Geometry of the proposed MPA at 28 GHz

Another author in [17] investigated the design of rectangular, circular, and triangular patch antenna at 28 GHz. The simulation results show that the maximum antenna gain for a circular patch is 7.2258 dB. Similar to the previous works, this paper proposed the use of an MPA at 28 GHz for 5G wireless communication. With improved bandwidth and gain, the proposed MPA will be able to accommodate a high data bit rate and high speed in the frequency spectrum. The following is

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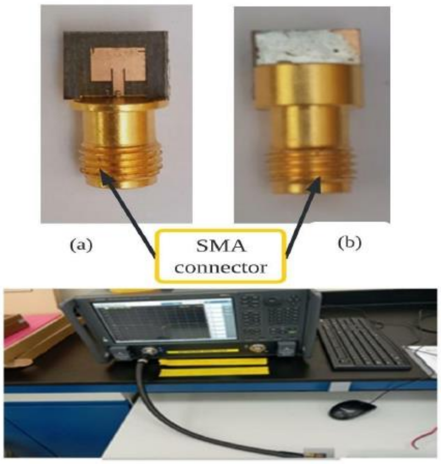
how this article is organized. Section I introduces the article, and Section II discusses the antenna design and configuration. Section III presented and discussed the experimental result. Lastly, Section IV concludes the article.

II. ANTENNA DESIGN AND CONFIGURATION

CST MWS® software is used to design and simulate the proposed MPA. The needed frequency of the mmW bands at 28 GHz with the best linear characteristics has been achieved through optimization to attain precise dimensions. Table. I give the dimensions of the substrate and the antenna patch. The MPA uses a transmission line and a slit square-shaped antenna, as seen in Fig. 1 and Fig. 2. Rogers Duroid RO5880^{TM} with $\epsilon r = 2.2$, $\tan \delta = 0.0009$ and thickness of 0.5 mm, is used to fabricate the antenna. The ZVB14 Vector Network Analyzer (VNA) from Rohde & Schwarz is used to measure the performance of the antenna. The proposed antenna is specifically designed and fabricated for one of the frequency bands that will be used in future 5G wireless communication.



(c)

Fig. 2: Photographs of the (a) front view fabricated prototype (b) back view fabricated prototype (c) S_{11} measurement setup

TABLE I: Parameters of the MPA

Parameters	Dimensions (mm)
W_s	7.24
L_s	6.3
W_p	4
L_p	3.3
h	0.5
L_f	3.1
W_f	0.8
W_g	0.1
L_g	2.95
Patch thickness	0.035

III. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed antenna was fabricated to validate all of the designs and simulations. Fig. 2(a) and (b) depict a prototype of the proposed MPA. Fig. 3 depicts a comparison of measured and simulated S_{11} of the proposed MPA at 28 GHz. The resonant frequency of the fabricated antenna is measured at 27.5 GHz and has a -10 dB measured impedance bandwidth of 2.685 GHz. The difference between the measured and simulated results can be related to fabrication precision and cable losses.

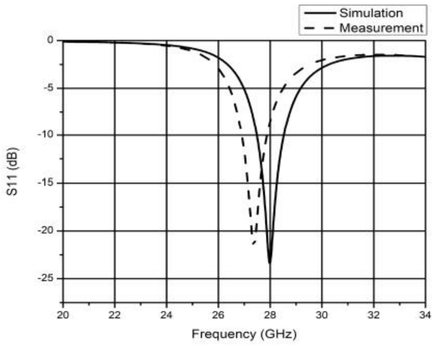
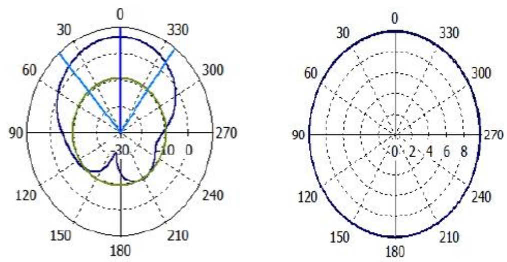


Fig. 3: The comparison of simulated and measured reflection coefficients at 28 GHz

Also, the radiation patterns of the MPA have been simulated at 28 GHz. Fig. 4(a) and 4(b) depict the MPA radiation patterns in the E-plane and H-plane. at 28 GHz the MPA achieved a directional radiation pattern in the E-plane and omnidirectional in the H-plane. However, the antenna achieved a high gain of 10.02 dBi. Fig. 5 depicts the 3D pattern of the proposed MPA at 28 GHz. The surface current distribution of the proposed MPA at 28 GHz is shown in Fig. 6. At 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and the vertical slit. Table II summarizes the measured bandwidth and directivity values at 28 GHz for the rectangular MPA. From the table, it can be seen that compared to the results obtained in the previous works listed in Table II, we observe that: (i) no fabrication and validation between simulation and measurement of their design, (ii) the proposed antenna achieves improved results in terms of bandwidth, return loss and directivity and (iii) the obtained measured values are similar to those given at 28 GHz and provided a high bandwidth of 2.685 GHz.



(a) (b)

Fig 4: Radiation patterns at 28 GHz (a) E-plane (b) H-plane

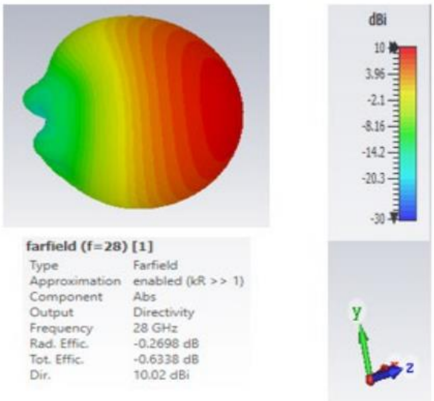


Fig 5: 3D pattern at 28 GHz

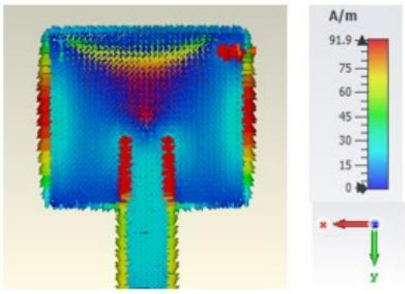


Fig 6: Current distribution at 28 GHz.

TABLE II: Comparison of the Bandwidth & Directivity of Different MPA

Ref	Resonance Frequency (GHz)	S_{11} (dB)	Bandwidth (%)	Directivity (dBi)
[14]	28.00	-16.7	3.36	10
[15]	27.09	-42.6	6.02	10.95
[16]	28.00	-35.6	7.86	12.87
[17]	28.00	-17	-	6.9214
This work	28.00	-21.4	9.59	10.02

IV. CONCLUSIONS

Applications of mmW necessitate MPA with improved performance in terms of speed, size, data rate and efficiency, requiring the use of enhancement techniques. This study proposes a new antenna design at 28 GHz for the 5G mobile communication network. The proposed MPA at 28 GHz has a measured return loss of -21.37 dB, a bandwidth of 2.685 GHz and a directivity of 10.02 dBi.The proposed MPA has significantly improved gain and bandwidth as compared with the previous literature due to its compact size which can be used for 5G mobile communication.

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Bandwidth enhancement of millimeter-wave microstrip patch antenna array for 5G mobile communication networks

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ABSTRACT

This paper proposed enhancing the bandwidth of a millimeter wave microstrip patch antenna (MPA) and its array for a 5G mobile communication network. The proposed antenna is designed and fabricated on a Rogers RT Duroid 5,880 substrate with a standard thickness of 0.5 mm, a relative dielectric constant of 2.2, and a tangent loss of 0.0009. With a center frequency of 28 GHz, a measured return loss of -21.37 dB, a bandwidth of 1.14 GHz, and a gain of 6.27 dBi, the proposed single element operates in the local multipoint distribution service band. The proposed antenna is designed and manufactured as an array of 1×2 and 1×4 elements. The 2-element MPA array has a measured bandwidth of 1.207 GHz and a gain of 7.76 dBi, higher than that of a single element. The 4-element MPA array achieved a measured bandwidth of 2.685 GHz and a gain of 9.87 dBi, which is higher than the 2-element and single-element arrays at 28 GHz. This demonstrates that the array of antennas improves gain and bandwidth significantly. Hence, the proposed antenna and array are suitable for 5G mobile communication networks due to their small size.

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1. INTRODUCTION

The requirement for extremely high throughput and more effective communication technology had already resulted in a significant expansion of wireless communication over time. When comparing fifth-generation (5G) base stations to their fourth-generation (4G) counterparts, for example, mobile devices require higher bandwidth [1]. Improved antenna systems are needed to meet the flexibility standards of designs, high gain, and enhanced bandwidth of operation for 5G [1], [2]. Since 5G communications require higher bandwidth, many frequency bands, including 28 GHz, 38 GHz, V band, and E band (71-76 GHz, 81-86 GHz, and 91-93 GHz), can be utilized [3].

A new age of technical development is being ushered in by 5G. The need for communication is shifting globally, and 5G has the potential to revolutionize civilization. It can be used for applications in autonomous driving, robotics, aviation, and the medical field owing to its data transmission rates of more than 1 Gbps [4], [5]. The pioneering spectrum bands for the 5G deployment have been identified as 680 MHz, 3.5 GHz, and 26/28 GHz [5]. To that end, many techniques that can enable 5G communication have been proposed in the literature. The slots technique, antenna array technique, defective ground plane structure, and metamaterial have all been applied to enhance performance parameters to satisfy the demands of 5G technology [6]–[8]. The millimeter-wave (mm-Wave) antenna is an important element of the 5G communication system microstrip antennas have been widely used to date due to their advantages of being compact, lightweight, and simple to integrate which are a good fit for usage in a range of wireless applications, including those for aviation, satellite communication, missiles, and medical applications [9]–[13]. Moreover, it comes with the disadvantage of lower bandwidth which can be enhanced utilizing various designed methods [14], [15] and losses caused by the surface wave; numerous works have been performed to utilize it. Even so, these techniques significantly increase complexity and cost [16]. Similarly, for mm-wave 5G applications, several printed antennas were proposed employing various techniques [17]–[20]. The feeding technique is one of the significant characteristics used to increase impedance bandwidth. However, the feeding method varies depending on antenna fabrication, price, and working mechanism with additional radiation, together with impedance matching [21].

Recently, most researchers presented various antenna design techniques for 5G applications. Antenna arrays designed for the mm-wave band were implemented on mobile handsets, but their structures all seem to be three-dimensional, creating incorporation challenges [22]–[24]. Array antennas, such as patch, slot, Vivaldi, and quasi-Yagi antennas were designed in a variety of configurations in [25]–[28]. Aghoutane *et al.* [12] proposed a broadband square slotted 2×1 slotted patch antenna array for 5G cell phone applications at 30 GHz. Similarly, Hasnaoui and Mazri [1] designed and simulated a rectangular patch array antenna for mm-wave applications. Likewise, Zafar *et al.* [4] proposed a spherical beam steering antenna design for next-generation mobile devices. According to Sohail *et al.* [29], an array of 1×4 antennas are presented utilizing Rogers RT/duroid5880 material, the results of the proposed arrays obtained indicate that the linear array has greater gain than the planar array, however, the planar array has superior bandwidth and return loss. Bangash *et al.* [30] proposed a patch antenna array for mm-wave applications.

Following this trend, to support 5G wireless communication, this paper proposes using a variant of the microstrip patch antenna (MPA) array at 28 GHz. With improved bandwidth and gain. The proposed MPA array would be capable of handling high data bit rates and high-frequency spectrum speeds.

2. ANTENNA DESIGN METHOD

The antenna employs Rogers RT 5,880 with εr=2.2, tan δ=0.0009 and thickness, h=0.5 mm. As shown in Figure 1(a), the MPA employs a slit square-shaped antenna with a transmission line. The antenna was designed and fabricated at 28 GHz. The array is used to improve the bandwidth and gain of the proposed antenna. The designed array has been completed using an array approach as shown in Figure 1(b) and (c) array of 1×2 and 1×4 elements a microstrip feeding method is used for the design antennas. The fabricated prototype of the single-element, an array of 1×2 and 1×4 of the proposed antenna is shown in Figures 1(d)-(f) respectively. Theoretical calculations are used to determine the actual size of the rectangular patch antenna. In (1)–(4) of the transmission and cavity model of the MPA are used in the design of the antenna [31]–[33].

Specifically, the patch length is below *λ/2* in other to allow the fundamental TM_{10} mode. Where λ is the wavelength expressed as $\lambda o/\sqrt{\varepsilon\ reff}$ and λo which demonstrates free space wavelength while εreff indicates effective dielectric substrate. The length and width of the patch are increased on each end by a distance ΔL, expressed as (1):

$$\Delta L = 0.412h\,\frac{(E_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(E_{eff}-0.264)\left(\frac{W}{h}+0.8\right)} \quad (1)$$

Where h expressed the thickness of the substrate and W indicates the patch width. The patch effective length, Leff is expressed as (2):

$$Leff = L + 2\Delta L \quad (2)$$

Where L represents the patch length. Moreover, for a resonance frequency, f_o the patch effective length is expressed as (3):

$$L_{eff} = \frac{c}{2fo\sqrt{E_{eff}}} \quad (3)$$

Likewise, patch width antenna is expressed as (4):

$$W = \frac{c}{2fo\sqrt{\frac{E_r+1}{2}}} \quad (4)$$

where $c=3\times10^8$ m/s is the speed of light.

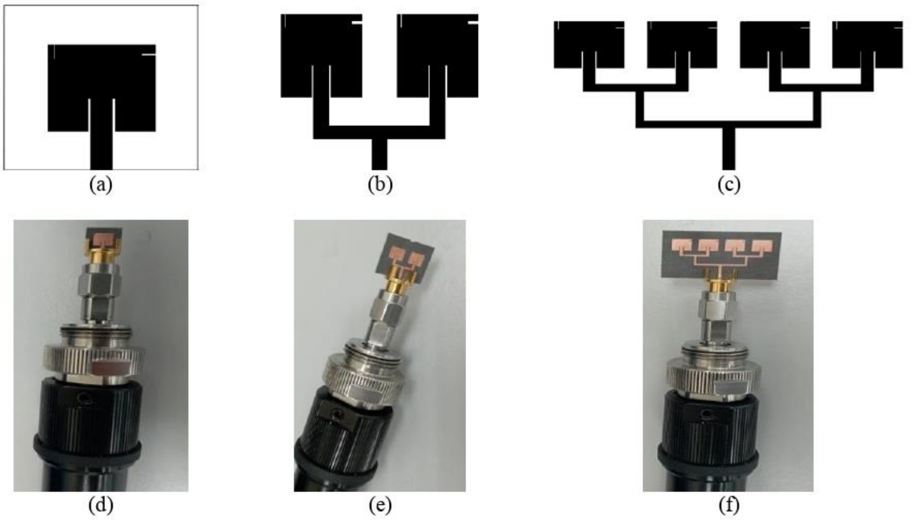

Figure 1. Design and prototype of the proposed MPA at 28 GHz (a) single element MPA, (b) MPA array of 1×2 elements, substrate size is 10.3×14.2 mm, (c) MPA array of 1×4 elements, substrate size is 14.3×26.2 mm, (d) prototype of single element, (e) prototype of 1×2 elements, and (f) prototype of 1×4 elements

The dimensions of the MPA are substrate width=7.24 mm, substrate length=6.3 mm, patch width=4 mm, patch length=3.3 mm, substrate thickness=0.5 mm, patch thickness=0.035 mm, feed length=3.1 mm, feed width=0.8 mm, slit width=0.1 mm, slit length=2.95 mm.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed antenna array was modeled using CST microwave studio. The simulation was validated by comparing the results obtained after fabrication to the measured results. The parameters under consideration are reflection coefficient, surface current distribution, radiation pattern and gain.

3.1. Single element MPA

The simulated and measured reflection S_{11} of the single element MPA at 28 GHz is shown in Figure 2. According to the figure, the proposed antenna operates at 28 GHz and has a simulated reflection coefficient (S_{11}) of -23.7 dB. The resonant frequency of the fabricated antenna is measured at 27.5 GHz with S_{11} of -21.37 dB and a bandwidth of 1.14 GHz that ranges from 26.96 GHz to 28.1 GHz. The difference between measured and simulated resonant frequencies can be attributed to fabrication tolerances and cable losses. Likewise, the radiation patterns of the single-element MPA have been simulated at 28 GHz. Figure 3 shows the radiations patterns of the single-element MPA in the E-plane and H-plane at 28 GHz. From Figure 3(a), it can be observed that the radiation patterns at the resonant frequency of 28 GHz in directional in the E-plane and omnidirectional in the H-plane as shown in Figure 3(b). Furthermore, Figure 4 depicts the surface current distribution of the single-element MPA at 28 GHz. It can be seen that at 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and vertical slit. However, the antenna achieved a high gain of 6.27 dBi.

3.2. MPA array of 1×2 elements

Figure 5 shows the simulated and measured S_{11} for 2-element array MPA, showing above 28 GHz with simulated S_{11} of -31.07 dB. The resonant frequency of the fabricated antenna is measured at 28.5 GHz with S_{11} of -22.37 dB and a bandwidth of 1.207 GHz that ranges between 27.84 GHz to 29.05 GHz. This demonstrates that the bandwidth of the 2-element MPA array exceeds that of the single element throughout the frequency range. The gain with a 1×2 MPA array is 7.76 dBi, which is a gain increase of 1.51 dBi. Furthermore, the radiation patterns of the single-element MPA have also been simulated. Figure 6 depicts the radiation patterns of a 2-element MPA array in the E-plane and H-plane at 28 GHz. The radiation patterns at the resonant frequency of 28 GHz are directional in the E-plane as shown in Figure 6(a) and omnidirectional in the H-plane as shown in Figure 6(b). This demonstrates an increased bandwidth and gain over the single-element MPA. Moreover, Figure 7 depicts the surface current distribution of the proposed 1×2 MPA array at 28 GHz. It can be seen that at 28 GHz, the maximum surface current is directed around the edges of the patch, feedline and vertical slit.

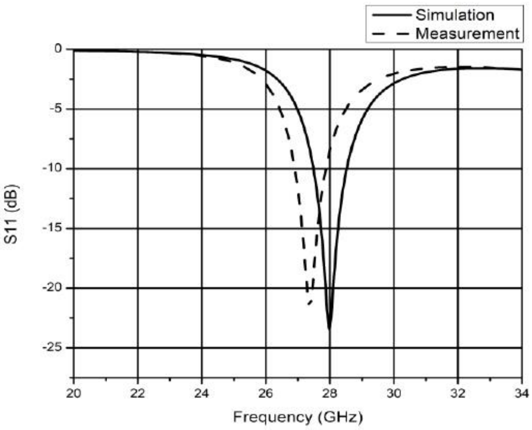

Figure 2. Simulated and measured S_{11} of the single element MPA

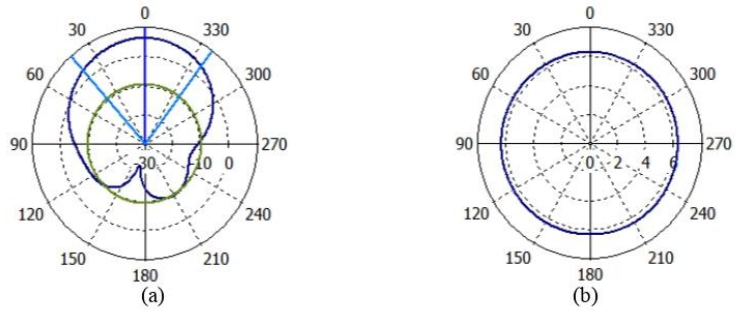

Figure 3. Radiation patterns of the single element MPA (a) E-plane and (b) H-plane

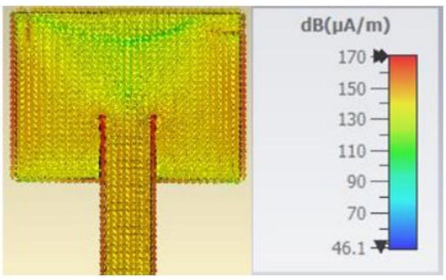

Figure 4. Surface current distribution of the single element MPA

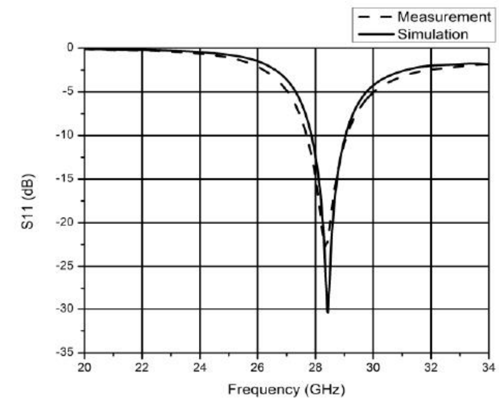

Figure 5. Simulated and measured S_{11} of the MPA array of 1×2 elements

(a) (b)

Figure 6. Radiation patterns of the MPA array of 1×2 elements (a) E-plane and (b) H-plane

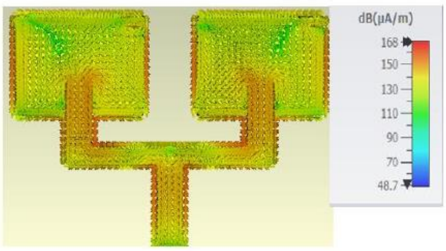

Figure 7. Surface current distribution of the MPA of 1×2 elements

3.3. MPA array of 1×4 elements

Figure 8 shows a comparison of simulated and measured reflection coefficients for the 4-element array MPA, the proposed antenna resonates at 28 GHz and with a simulated S_{11} of -30.71 dB. The fabricated antenna has a resonant frequency of 27.8 GHz, with a measured S_{11} of -19.37 dB, and a bandwidth of 2.685 GHz, which ranges between 26.66 GHz and 29.35 GHz. At 28 GHz, the bandwidth of the 4-element MPA array is greater than that of the 2-element and single-element MPA arrays. The single-element MPA has a gain of 6.27 dBi and the 2-element MPA array has a gain of 7.76 dBi. The gain with a 1×4 MPA array is 9.87 dBi, which is a 2.11 dBi increase over a 1×2 MPA array. Furthermore, the radiation patterns of the single-element MPA have also been simulated. Figure 9 depicts the radiation patterns of a 4-element MPA array in the E-plane and H-plane at 28 GHz. It is observed that the radiation patterns at the resonant frequency of 28 GHz are directional in the E-plane as shown in Figure 9(a) and omnidirectional in the H-plane as shown in Figure 9(b). Similarly, this design has demonstrated an increased bandwidth and gain over the single-element MPA and 12 MPA arrays. As a result, when compared to the 2-element patch antenna and the single patch antenna, the directivity and gain are significantly increased. Moreover, Figure 10 depicts the surface current distribution of the proposed 1×4 MPA array at 28 GHz. It can be seen that at 28 GHz. This demonstrates the suitability of this antenna design for use in 5G applications.

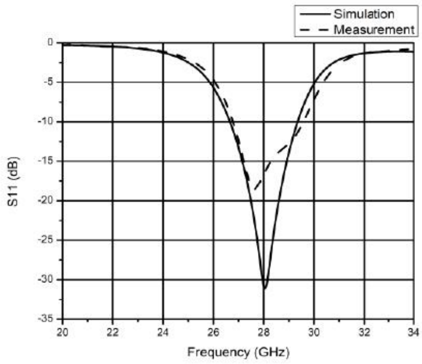

Figure 8. Simulated and measured S_{11} of the MPA array of 1×4 elements

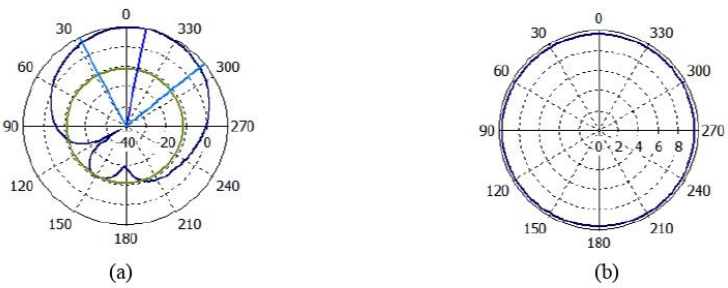

Figure 9. Radiation patterns of the MPA array of 1×4 elements (a) E-plane and (b) H-plane

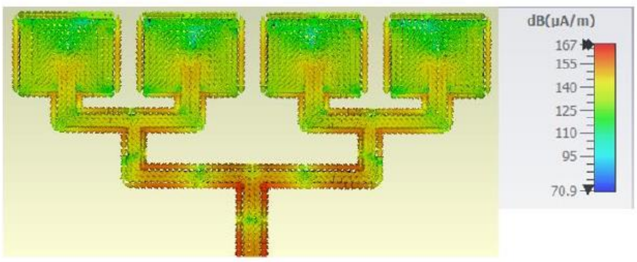

Figure 10. Surface current distribution of the MPA of 1×4 elements

In addition, Table 1 summarizes the measured bandwidth and directivity values at 28 GHz for the MPA 1, 2, and 4 rectangular parallel feed arrays. According to the table, increasing the number of elements increases gain, bandwidth and directivity implying that the four-element patch antenna has high characteristics. When the results were compared to the previous work, which is illustrated in Table 2, the following conclusions were reached: first, there is no fabrication or validation of their design between simulation and measurement. Second, the proposed array antenna achieves better results in terms of bandwidth, reflection coefficient and directivity; and finally, the measured values obtained are comparable to those obtained at 28 GHz and provide high bandwidth (2.685 GHz).

Table 1. Summary results of single element, 1×2 and 1×4 array MPA

Antenna design	Measured S_{11} (dB)	Measured bandwidth (GHz)	Directivity (dBi)
Single element	-21.37	1.14	6.27
1×2 MPA	-22.37	1.207	7.76
1×4 MPA	-19.37	2.685	9.87

Table 2. Comparison with previous work of different 1×4 array MPA

Ref	Resonance frequency (GHz)	S_{11} (dB)	Bandwidth (GHz)	Directivity (dBi)
[29]	28.00	-16.66	0.94	10.00
[30]	27.09	-42.6	1.63	10.95
[1]	28.00	-35.6	2.2	12.87
[4]	28.00	-17.00	-	6.9214
This work	28.00	-30.71	2.685	9.87

4. CONCLUSION

MPA with increased performance in terms of speed, size, data rate, and efficiency are required for mm-wave applications. As a result, enhancement methods are required. This study proposes a new antenna array design for the 5G mobile communication network at 28 GHz. A four-element antenna array's bandwidth and directivity increased when compared to single-element and two-element array antennas, as demonstrated by the simulated and measured results comparison. The 5G antenna and array can be used for future 5G mobile communications due to their compactness and small size.

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