

Design and Performance Analysis of PIFA Microstrip Antenna Array at mmWave for MIMO Cellular Radio Communication



Teshome Watro Wata

A Thesis Submitted to

The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Master of
Science Degree in Electronics and Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2022

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled “Design and Performance Analysis of PIFA Microstrip Antenna Array at mmWave for MIMO Cellular Radio Communication” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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ACKNOWLEDGEMENT

First and foremost, I would like to express my gratitude to God for allowing me to complete my thesis. I'd like to express my sincere gratitude to my advisor, Dr. Rajaveerappa Devadas, who has encouraged me throughout my thesis work and sacrificed his valuable time to encourage me, to work in my own way, and to give me the freedom to explore deeply in this study; without his valuable assistance, it would not have been possible to achieve the study's ultimate goal.

My thanks also go to Mr. Garoma Gerbi, my co-advisor, for his input on papers and other key issues in this thesis work. I'd also like to express my gratitude to the Electronic and Communication (ECE) department head, Mr. Gemechu Dengia (Senior Lecturer MSc.), and laboratory staff members for encouraging me, making open computer labs for discussion, and creating a very friendly working environment, as well as making me feel very welcome during my thesis work.

I'm also grateful to my loved ones, particularly my mother, friends, and classmates, who have always encouraged and supported me in finishing this thesis. I am grateful to everyone who has supported me throughout my work, providing me with encouragement and essential assistance.

Finally, I would like to express my heartfelt gratitude to Engida Esayas, my beloved wife, and my twin children Yididiya and Yitbarek Teshome. I am able to complete this task only because of your unwavering support, unconditional love, and valuable time. In my life, you are very important.

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LIST OF SYMBOLS

ϵ_r	dielectric constant of substrate
f	operating frequency
ϵ_{eff}	effective dielectric constant
L_{eff}	effective length of the patch
c	free space velocity of light, which is 3×10^8 m/s
W_p	width of the patch
L_p	length of the patch
λ	Wavelength
e	Efficiency of Antenna
σ	conductivity of the conductor
D	directivity of the patch antenna
η	radiation efficiency
W_s	width of shorting pin
y_o	Feed Point position

ABBREVIATIONS

AWS.....	Enhanced Wireless Services
DAA.....	Detect and Avoid
DGS.....	Defected Ground Structure
E field.....	Electric field
EBG.....	Electromagnetic Band Gap
FDTD.....	Finite Difference Time Domain
FR-4	Flame Retardant 4
Gbps.....	Giga bit per second
GPS.....	Global Positioning Systems
H field.....	Magnetic Field
HF	High Frequency
HPBW.....	Half Power Beam Width
ICT.....	Information and Communications Technologies
IFA.....	Inverted F-Antenna
ISI.....	Inter symbol Interference
LAA	Licensed Assisted Access
LMDS	Local Multipoint Distribution Service
MBAs.....	Multibeam Antennas
MIMO.....	Multiple Input Multiple Output
MMW.....	Millimeter-Wave
MSAs	Microstrip Array Antenna
MU-MIMO.....	Multi-user Multiple Input Multiple Output
NR.....	New Radio
OTA.....	Over the Air

PSTN.....	Public Switching Telephone Network
PIFA.....	Planar Inverted F-Antenna
PML.....	Perfect Matched Layer
RF.....	Radio Frequency
RL.....	Return Loss
SAR	Specific Absorption Rate
SNR.....	Signal to Noise Ratio
SU-MIMO.....	Single-user Multiple Input Multiple Output
TEM.....	Transverse Electric- Magnetic
Tx/Rx.....	Transmitter/Receiver
VSWR.....	Voltage Standing Wave Ratio
WiMAX.....	Worldwide Interoperability for Microwave Access
WLANs.....	Wireless Local Area Networks

ABSTRACT

Patch antennas, which are a major component of modern wireless communication systems, have played a key role in this evolution. Especially compared to conventional microwave antennas, microstrip antennas are smaller, lighter, easier to build, less costly, and easier to integrate into cellular networks. mmWave MIMO Antenna Arrays with beam forming improve the overall user experience by greatly boosting network coverage and capacity while simultaneously minimizing cellular communication interference with the right base station antenna configuration. The Planar Inverted F-Antenna (PIFA) Microstrip Antenna Array is designed in this thesis at mmWave for MIMO Cellular Radio Communication with acceptable bandwidth enhancement at V-band frequency. For mmWave cellular radio communication systems, the Antenna Array design for MIMO PIFA Antenna Array topologies can be used to increase channel capacity and achieve the required effective gain of the Antenna. In this thesis work, modelling was done at various levels of design parameters for a range of PIFA antenna designs. The single element, 1X4 and 4X4 PIFA element level have been built, modelled, and proposed for use in current and future cellular communication technology. Different antenna parameters such as gain, directivity, return loss, polarization, beam width, band width, and radiation patterns are studied and modelled for the PIFA Antenna Array at V-band (60 GHz) operating frequency. In this thesis, a probe-fed PIFA Antenna with infinite ground plane in FEKO, one should create a planar multilayer substrate and set a ground plane with space between the elements to reduce the mutual coupling. Then create wire probes between patches and ground plane. The radius of the wire probe (wire segment radius) is set to be 0.5mm. At V-band, the proposed PIFA Antenna Array achieves Gain 6.25 dBi, 6.67 dBi, and 12.14 dBi, Directivity 10.34 dBi, 12.51 dBi, and 15.12dBi, VSWR 1.01, 1.03, and 1.18, Band width of $S_{11} \leq -10\text{dB}$ was 3.81GHz, 3.22GHz, and 2.69 GHz, and Return loss -46.1 dB, -48.02dB, and -47.23dB. The 4X4 PIFA Antenna Array outperformed the single and 1X4 PIFA in the majority of performance criteria in the evaluation of the proposed alternative PIFA configurations. When different steering angles are used with the same substrate thickness and the PIFA element is increased, the directivity of the PIFA Antenna Array rises marginally, improving bandwidth efficiency. The entire PIFA Antenna designs discussed was strong competitors for mmWave 5G wireless communications and other applications.

Key words: Cellular, PIFA, IFA, mmWave, CADE-FEKO, MIMO, band width, beam width

CHAPTER ONE

1. Introduction

1.1 Background of the Study

Internationally, information and communications technologies (ICT) industry connects, and manages billions of devices. The increased need for faster data speeds and the convenience of mobile communication has resulted in a slew of new concepts and technological advancements throughout the last generation. As a result, contemporary cellular networks are operating at or near their theoretical capacity limits within allocated spectrum. At the same time, accessible spectrum in classic frequency ranges (V-band) is sparse at best for densely populated regions such as downtowns, shopping malls, and airports. As a result, migration to higher frequency bands is inevitable in order to increase available capacity. The wireless industry has recently been urged to examine the mmWave spectrum for cellular communications due to recent advances in mmWave circuits and systems (Leszczynski, 2020).

The utilization of millimeter wave spectrum has recently been proposed due to its large spectrum availability, higher bandwidth, and high data rate and can handle larger user capacity compared with today's wireless systems (Nurul et al., 2019). Millimeter wave spectrum used for mobile communication is Local Multipoint Distribution Service (LMDS) band. LMDS uses a cellular infrastructure, with multiple base stations supporting point-to-multipoint communication to small customer transceivers. Millimeter wave spectrum use by LMDS ranges between 28–32 GHz (Nurul et al., 2019).

28 GHz was chosen as the frequency of operation of the antenna design as defined by researchers in (Nurul et al., 2019). In order to increase the channel capacity, utilization of massive MIMO system is needed in 5G wireless communication systems at both the transmitter and receiver along with some complex signal processing. Compared to single antenna, MIMO antenna has high Signal to Noise Ratio (SNR) resulted in higher data rate (Thotahewa et al., 2014).

The analysis was assumed that mobiles and base stations employ Omni-directional antennas. Directional high-gain antenna beams are used to overcome the high path loss at mmWave frequencies, but the sensitivity to misalignment of antenna beams, and the effect of link blockage due to environmental and mobile obstacles such as buildings and humans, remains primary

challenges for seamless coverage in large-scale mobile network deployments (El-jaafreh, 2019). The key to making mmWave cellular networks a reality is thus exploiting multi-antenna technology for robust and precise beam steering to overcome effects of blockage and beam misalignment caused by large and small-scale mobility, and provide seamless gigabit-per-second (Gbps) connectivity.

In 5G communication system, the devices can search an unoccupied spectrum in the form of base station downlink signals and takes the instruction from the cellular system. Cellular system is quite sophisticated and achieves high spectral efficiency. 5G systems were based on dynamic spectrum sharing such as detect and avoid (DAA) and the dynamic frequency selection. The smart MIMO antennas have the ability of beam formation and beam tracking (Chettri & Sazad, 2015). MIMO antenna possess of two unique properties switched beam pattern and adaptive array. In switched beam antenna pattern, the desired user is peaked and the interference are traced and tracked by switching the antenna beam. This unique property of smart antennas has the tendency to reduce interference and increase spectral efficiency. In switched adaptive array the desired user is peaked and the interference is null.

There was a 20-dB increase in power loss at frequencies less than 30 GHz, with no effect on transmitter-receiver distance. As a result, in 5G NR, it is suggested that the increased frequency range millimeter wave communication technology have been used. Blockage is a problem in mmWave technologies, and most propagation occurs in 'Line of Sight,' which can be mitigated by MIMO beam formation, which provides additional gain to compensate for signal attenuation. MIMO should be implemented on a much higher scale to provide sufficient gain. Small cell deployment and Licensed Assisted Access (LAA) are both possible with 5G NR heterogeneous networks based on mmWave and MIMO.

Installing of MIMO antenna in transmitter and receiver enhances network capacity. The mmWave frequency can offer utilization of underutilized spectrum by sensing and allocation. mmWave has an extremely short wavelength which can accommodate large number of antenna array in a small area which helps in realization of MIMO at base station and user terminal. These considerations lead to the deployment of MIMO antenna system. Antenna serves as one of critical component in any wireless communication system. An antenna with a suitable design can reduce system requirements while also improving overall performance. In general, the

antenna behaves as a transducer between guided wave and a free space. There are various types of antennas and they include wire antennas, aperture antennas, reflector antennas, lens antennas, micro strip antennas and array antennas (Tiwari & Verma, 2014).

Patch antennas have played a vital role in the evolution of current wireless communication networks. When compared to standard microwave antennas, microstrip antennas are smaller, lighter, easier to build, less expensive, and easier to integrate into cellular networks.

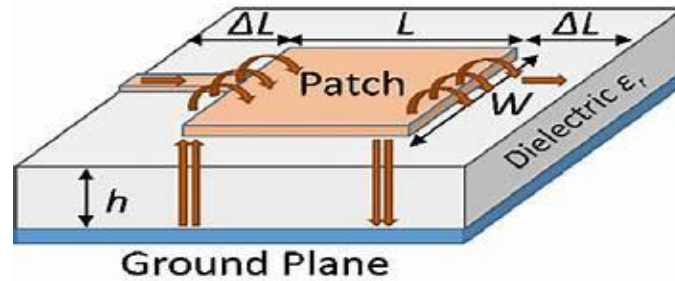


Figure 1.1: Microstrip Patch Antenna

The figure 1.1 determines the simple rectangular structure of the microstrip patch antenna with top patch, bottom ground plane and between top and ground plane dielectric material. The dimensions of the patch were width (w) and length (L), and h is the thickness of the dielectric material.

The desire for compact antenna has increased these days due to rapid decrease in dimensions of mobile devices (Loharia et al., 2016). Due to multiband properties and compact dimensions, planar Inverted F-Antenna is relatively good alternative to be used in mobile devices. The planar inverted F-antenna has been devised from Inverted F-Antenna (IFA). The Inverted F-Antenna suffered from a narrow bandwidth, due to which the wire radiator was replaced by a shorting plane in Planar Inverted F-Antenna. PIFA shows improved performance with a compact size (Loharia et al., 2016).

With the rapid development of the telecommunications industry and the growing market for more advanced cellular radio transmission qualities like increased network speeds and low network congestion, the current generation of telecommunication systems would no longer being able to satisfy the requirements of consumers. With this over all problems have been studied and there was so many researches done to enhance the bandwidth of PIFA antenna at higher frequency band (V-bands). Since PIFA is lightweight and allows multiband and

broadband operation with customizable dimension, this research proposes a novel design of PIFA antenna at mmWave for MIMO cellular radio communication.

These antennas are suitable for devices with limited space. Since PIFA produces minimal backward emission, incident electromagnetic absorption is minimized. It is designed in a way which enables it conscience. Due to its compactness, shortened length, and easy implementation, PIFA can be used in a wide range of applications, include cellular and wireless communications (Gkonis et al., 2020). The appropriate circular polarisation, easy feed, simple manufacturing, and easy installation in a portable terminal are really just a few of attractions of PIFA.

By widening the ground plane, the single PIFA design has been expanded to MIMO antennas. Meanwhile, the other PIFA parts are added to the opposite side of the ground plane using the same dimensions. Adjusting the width of the ground plane to make the spacing between the antenna elements adequate is a simple way.

1.2 Statement of the Problem

Cellular technologies are becoming increasingly cell-centric, which is problematic if we wish to connect at high speeds. As a result, one must migrate from cell-centric to user-centric cellular networks by utilizing beam forming technology. Then, when used in conjunction with the appropriate base station antenna layout, an mmWave MIMO antenna array with beam forming improves the entire user experience by dramatically boosting network coverage and capacity while simultaneously minimizing interference. The fixed frequency with un-adjustable polarization and single band frequency of operation are two contemporary cellular communication challenges with base station antennas. As a reason, designing an adaptive multiband antenna is essential to handle many additional problems. As a consequence, the goal of this thesis was to build a PIFA array antenna for cellular communication at the V-band frequency and MIMO configuration.

- Other issues, like as the cellular radio transitions reduced gain, can be addressed by using several antenna elements in a linear or phased array configuration. It is worth noting that tuning dozens of antenna characteristics is required while creating an array of stacked patch antennas. As a result, single element, one by four, and four by four elements of mmWave

planar inverted F-antennas applicable for MIMO cellular radio communication were built using coaxial feeding approaches in this study, and the performance was evaluated.

1.3 The Study's Objectives

1.3.1 General Objective

The main objective of this thesis work is to design a Planar Inverted F-Antenna (PIFA) Microstrip Antenna Array at mmWave for MIMO Cellular Radio Communication.

1.3.2 Specific Objectives

The below are the specific objectives of this research work:

1. To develop a mathematical analysis (cavity model) for the design of a single PIFA antenna working at the mm - wave frequency.
2. To design a PIFA array antenna for cellular radio communication at the mmWave frequency.
3. To look into the effect of PIFA design parameters on mmWave cellular radio communication performance.
4. To investigate and examine the effectiveness of single element, 1X4 and 4x4 PIFA arrays in terms of the dimensions such as shortening plate, ground plane width and length, patch width, patch length, and height.
5. To analyze performance parameters of PIFA array antenna such as VSWR, gain, return loss beam width, radiation pattern (E and H-plane) and band width.

1.4 Significance of the Study

There have been so many studies on designing PIFA antenna for various purposes, but one thing that stands out here is that PIFA antenna has such a huge amount of potential as a base station for cellular radio communication. As a consequence, the PIFA design for the base station was used in this thesis to boost effectiveness of key design characteristics. The antenna array design for MIMO PIFA antenna array configurations can be utilized to enhance the channel capacity and achieve the needed effective gain of the antenna for mm - wave cellular radio communication systems. There are a variety of PIFA antenna designs, and modeling was done at various levels of design parameters. The single element, 1X4 and 4X4 PIFA array antenna designed, modeled, and proposed for contemporary and future conventional cellular communication technology at the mmWave frequency band have been the primary priority of

this thesis. The proposed design has a better directivity and a greater specific absorption rate (SAR) values, making it suitable for mobile radio communication.

1.5 Study Scope and Limitation

Due to its unique design, operation, and planarity, a Planar Inverted F-Antenna (PIFA) was selected. In this study, the performance evaluation of parameters would be investigated by modifying the characteristics of the PIFA array antenna for base station. As a consequence, the focus of this thesis would be on PIFA designs that really are suitable with mmWave (5G and beyond) for MIMO cellular radio communication.

As a result, the scope of this thesis was limited to the specific objectives, which would be investigation of something like the effectiveness of PIFA design parameters at mmWave for MIMO cellular radio communication. As an outcome, the mathematically calculated and designed antenna was simulated using simulation software. This was accomplished by software modeling; therefore the mathematically modeled and planned antenna was designed and tested using Matlab, CAD-FEKO software.

1.6 Thesis Structure

The rest of this thesis is organized as follows:

The chapter 2 was solely dedicated to a review of the PIFA antenna, basic review of feeding techniques and antenna parameter, as well as the fundamentals of cellular communication and MIMO antenna designs. The design of single, one by four and four-by-four elements of the PIFA antenna, which operates in the mmWave frequency band, is presented in Chapter 3. The findings of simulation results are recorded and interpreted for the particular aspect of single, one by four and four by four elements Planar Inverted F-Antennas are presented in Chapter 4. Finally, the thesis ends with conclusion and recommendations.

CHAPTER TWO

2. REVIEW OF THE LITERATURE

2.1 Introduction

Wireless communication systems' electrical components are designed to be lightweight and light for accessibility and performance while still providing sufficient performance and efficiency. Antennas are major elements of mobile devices, and they must fit within the space limitations imposed by manufacturing specifications. The planar inverted-F antenna (PIFA) is a common and attractive choice for miniaturized antennae in cellular phones to satisfy this requirement. The PIFA design can be modified and extended to cover multiple frequency bands, as well as those in use by mobile phones, Wi-Fi, and Bluetooth. The Enhanced Wireless Services (AWS) spectrum downlink frequency range is covered by this antenna. The antenna's impedance matching qualities are evaluated using S-parameters, and the far field radiation pattern is modeled.

2.2. Planar Inverted F-Antenna

Planar Inverted F-Antenna is used in a wide range of applications because it is easy to design and fabricate. The antenna is attractive due to its low-profile conformal design, relatively low cost, and very narrow bandwidth. For applications where size, weight, cost, performance, ease of installation and aerodynamics are constraints, low profile antennas are needed. Aircraft, spacecraft, satellite and missile applications and recently mobile radio and wireless communications demands (Zhang, 2007).

To meet the requirements planar inverted F-antenna can be used because of it has numerous advantages such as small structure, multiband behavior, low cost, mechanically robust and reduced absorption rate as compared to other conventional antennas. Planar Inverted F Antenna has reduced Specific Absorption Rate (SAR) value; hence fewer radiations are illuminated towards user's head and body (Rathod, 2010).

Planer Inverted F- Antenna in its simplest configuration consists of a radiating patch on one side of a dielectric substrate, which has a ground plane on the other side. The patch conductors usually made of copper or gold can be virtually assumed to be of any shape. However, conventional shapes are normally used to simplify analysis and performance prediction. The

radiating elements and the feed lines are usually hinged on the dielectric substrate (Pg & College, 2019).

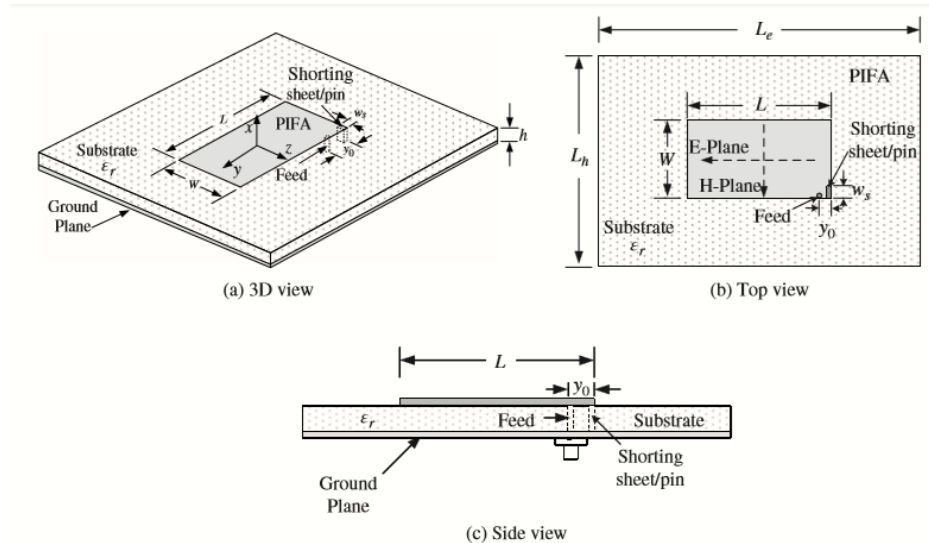


Figure 2.1: Basic PIFA Geometry (Rathod, 2010)

In figure 2.1, the geometry of PIFA, design variables for the antenna are the length, width, and height of the patch, the width and location of shorting plate, and feed point location. A coaxial cable with a centre conductor that extends beyond the end of the outer conductor is the feed wire for PIFA. The outer layer of conductor is soldered to the ground plane at the selected feed point.

2.3. Advantages

2.3.1. Advantages of PIFA Antennas

- small size
- light weight
- low-profile
- simple fabrication
- relatively low specific absorption rate (SAR) and
- provides good efficiency
- It can be realized in a very compact form, desirable for personal and mobile communication hand held devices.
- It allow for dual and triple band operations
- It can be hiding into the housing of the mobile while comparable to whip/rod/helix antennas.

- It reduces the backward radiation toward the user's head, minimizing specific absorption rate (SAR).
- Third advantage is that PIFA it exhibits moderate to high gain in both vertical and horizontal states of polarization.

2.3.2 PIFA Challenges and Solutions

Several modifications have been suggested to obtain a trade-off between size, bandwidth and other properties of a PIFA (Thu et al., 2020).

A. Techniques to Increase the Bandwidth for the PIFA

The most frequently used method to broaden the bandwidth is to raise the height of the shorting plane i.e increase the volume. Size of the ground plane affects Bandwidth very much. The bandwidth of a PIFA can be improved by modifying the size of the ground plane i.e. reducing the ground plane can broaden the bandwidth of the antenna system. Several slits at the ground plane edges can be inserted to lower the Q factor of the structure, which results in increase of bandwidth. Bandwidth enhancement of a PIFA can also be achieved by several efficient approaches, namely using dual resonance by additional patch that is adding capacitive load (Ojaroudi Parchin et al., 2020), loading dielectric with high permittivity (R.K. & Suryakanth, 2015), attaching chip resistor that is increasing loss term.

I. PIFA Dimensions

PIFA size can be reduced by shortening the antenna dimensions. However, by using this approach the impedance at the antenna terminals is affected which makes the radiation resistance reactive as well. By applying capacitive top loading, this can be compensated. This loading result in resonance length reduction from $\lambda/4$ to less than $\lambda/8$ but this is achieved at the expense of good matching and bandwidth. By adding a plate (parallel to the ground) produce a parallel plate capacitor to be used as capacitive load (R.K. & Suryakanth, 2015).

II. Resonant Frequency

To approximate the resonant frequency of PIFA following relation is used (Perez-Quintana et al., 2020):

$$L_p + W_p - W_s = \frac{\lambda}{4} \quad (2.1)$$

When, $\frac{W_s}{L_p} = 1$ then, $L_p + H = \frac{\lambda}{4}$

$$\text{When, } W_s=0 \text{ then, } L_p + W_p + H = \frac{\lambda}{4} \quad (2.2)$$

Where L_p and W_p are length and width of patch, W_s is width of shorting plate H is height of shorting plate by creating an open slot the frequency gets reduced. This is because currents are flowing at the edges of the created slot, therefore the frequency and antenna dimensions gets reduced significantly due to a capacitive loaded slot. Similarly, by making slots in the patch, two or more frequency band operation can be achieved. Modifying the width of the patch also affects the selection of the resonant frequency. The width of the shorting plate of the PIFA acts as governing factor for its resonant frequency. Resonant frequency decreases with the decrease in plate width, W_s . PIFA's are made of just quarter wavelength whereas micro-strip antennas are conventionally made of half wavelength dimensions, By analyzing bandwidth and resonant frequency, characteristics of the antenna can be easily improved by determining the site for feed point (Kumar et al., 2013), at which reflection coefficient is to be minimum.

The Inverted F antenna has transformed the horizontal element from a wire to a plate resulting in the so-called Planar Inverted-F Antenna (PIFA). It has a self-resonating structure with purely resistive load impedance at the frequency of operation. PIFA is an antenna, which is not only small but also has wide bandwidth and high efficiency. Variation of length, distance and location of the feed and shorting point, height of the radiator etc. affects the electrical performance of these antenna structures (Zhao et al., 2019). Typical configuration of PIFA is shown in fig. 2.1. The antenna is fed through feeding pin, which connects to the ground plane through the dielectric substrate. The shorting pin and shorting plate allows good impedance matching achieved with the patch above ground plane of size less than $\lambda/4$. Resulting PIFA structure is of compact size than conventional $\lambda/2$ patch antennas.

III. Efficiency

The efficiency of PIFA is reduced by all losses suffered by its structure in its environment, including: mismatch losses, ohmic losses, external parasitic resonances, edge power losses, transmission losses etc. The Inverted F antenna has transformed the horizontal element from a wire to a plate resulting in the so-called Planar Inverted-F Antenna (PIFA). It has a self-resonating structure with purely resistive load impedance at the frequency of operation. PIFA is an antenna, which is not only small but also has wide bandwidth and high efficiency. Variation of length, distance and location of the feed and shorting point, height of the radiator etc. affects the electrical performance of these antenna structures. Typical configuration of PIFA is shown

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2.4. Feeding Techniques PIFA Microstrip Patch Antenna

Resonators with feed lines are used to excite the fields of microstrip antennas. Feeding microstrip patch antennas can be done in a number of ways. There are two types of methods:

- 1) Getting in Touch
- 2) Avoiding direct interaction

RF power is delivered directly to the radiating patch via a connecting device such a microstrip wire in the contacting approach. To transfer power between the microstrip line and the radiating patch in the non-contacting system, magnetic field coupling is used. The four most often used feed mechanisms are microstrip lines, coaxial probes (both contacting systems), aperture coupling, and proximity coupling (both non-contacting schemes).

2.4.1. Microstrip-line Feed

A conductive strip is attached directly to the edge of the microstrip patch with this type of feed technology, as seen below. This feed design has the advantage of being able to etch the feed on the same substrate as the patch, resulting in a planar structure. The purpose of the patch's inset cut is to match the feed line's impedance to the patch without using any additional matching components (Zhao et al., 2019). The inset position is carefully managed to accomplish this. As a result, this is a simple feeding scheme since it provides for easy manufacture, modeling, and impedance matching. Surface waves and spurious feed radiation rise with increasing dielectric substrate thickness.

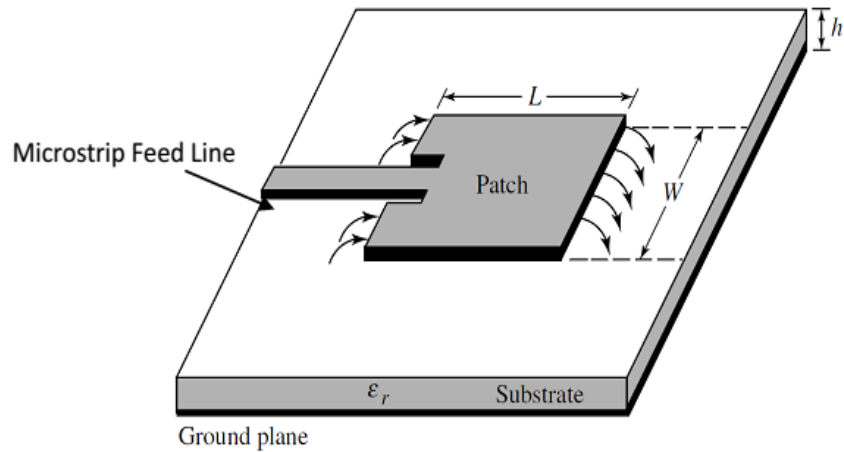


Figure 2.2: Microstrip Insert Feed (Zhao et al., 2019)

2.4.2. Coaxial Feed

Coaxial feed, often called probe feed, is commonly used to feed microstrip patch antennas. The inner conductor of the coaxial connector extends through the dielectric and connects to the radiating patch, as shown in Figure 2.3, while the outside conductor connects to the ground plane. The key benefit of this feeding technique is that it allows the feed to be positioned. This feed technique is simple to build and produces very little harmful radiation. Because a hole must be made in the substrate and the connector protrudes outside the ground plane, it is non-planar for thick substrates ($h > 0.02\lambda$), it has a limited bandwidth and is difficult to match. Furthermore, on thicker surfaces, the longer probe length makes the input impedance more inductive, causing matching issues. When utilized with a thick dielectric substrate that provides large bandwidth, both the microstrip line and coaxial feed suffer from a number of limitations, as indicated above.

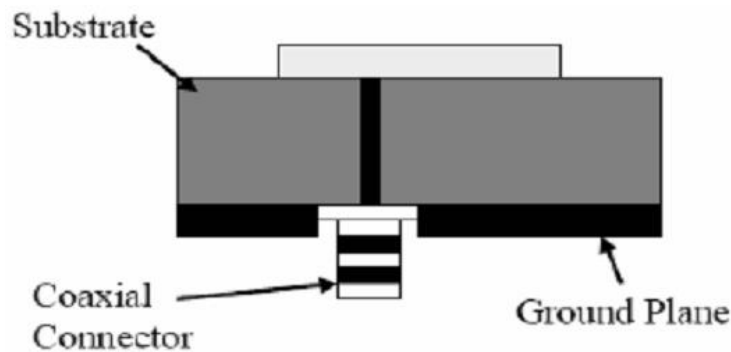


Figure 2.3: Coaxial Feed (Zhao et al., 2019)

2.4.3. Proximity Coupled Feed

This kind of feeding method is also known as the electromagnetic coupling approach. In the figure 2.4, the feed line was sandwiched between two dielectric substrates, with the surface layer perched on topmost one. This feed technique avoids erroneous feed radiation and gives extraordinarily high capacity due to the overall increase in the thickness of the microstrip patch antenna (as high as 13 percent). This method also allows for the use of two different dielectric mediums, one for the patch and the other for the feed line, to enhance individual performance.

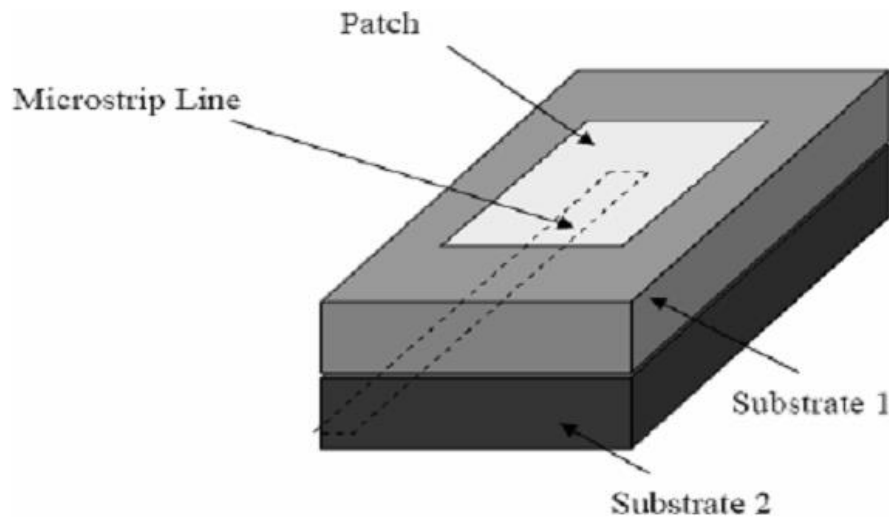


Figure 2.4: Proximity Coupled Feed (Zhao et al., 2019)

Adjusting the length of the signal source and the patch's width-to-line ratio can help with matching. The main disadvantage of this feed method is that it is difficult to construct due to the two dielectric layers that must be oriented appropriately. The total thickness of the antenna has also increased.

2.4.4. Aperture Coupled Feed

The ground plane protects the radiating region from the microstrip feed line in this type of feed technology, as shown figure 2.5. A slot or aperture in the ground plane connects the patch to the feed line. The coupling aperture is often centered under the patch because to the symmetry of the structure, resulting in reduced cross polarization. The form, size, and position of the aperture influence the amount of coupling from the feed line to the patch. The patch and the feed line are separated by the ground plane, which lowers available to generate. To maximize patch radiation, the bottom substrate is made of a thick, low-dielectric-constant material, while

the top substrate is made of a thin, high-dielectric-constant material. The main downside of this feed method is that it is challenging to make due to the multiple layers that raise antenna size.

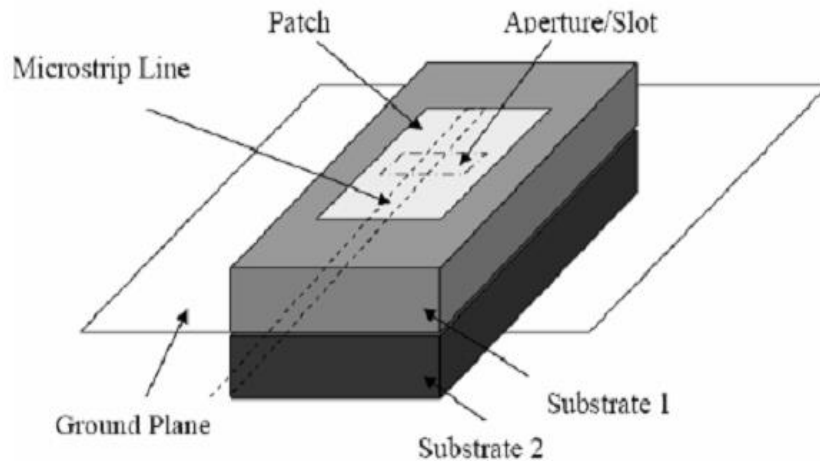


Figure 2.5: Aperture Feed (Rathod, 2020)

2.5. Different Methods of Analysis

- Transmission line model
- Cavity model
- Full Wave Analysis
- Finite Difference Time Domain Method

For the analysis of Microstrip patch antennas, the transmission line model, cavity model, and complete wave model (which includes significantly integral equations/Moment Method) are the most widely used models. The transmission line model is the most basic of them all, and while it gives useful physical data, it is also the least precise. The cavity model is more accurate and provides a greater grasp of the physical world, but it is also more difficult to use. Complete wave models, which are extremely accurate and versatile, can handle single elements, finite and infinite arrays, stacked components, low dimensional space elements, and coupling, among other things.

2.5.1. Transmission Line Model

The figure 2.6 illustrates the microstrip line feeding, microstrip antenna consists of two slots with width W and height h separated by a transmission line with length L . A microstrip is a non-uniform line comprised of two dielectric materials, most commonly the substrate and air.

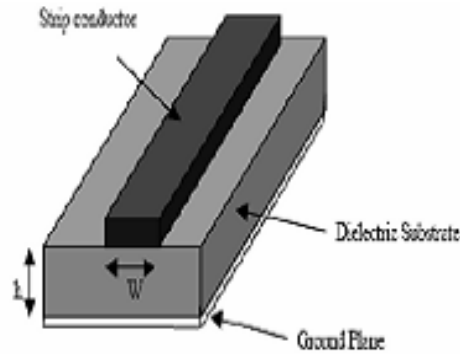


Figure 2.6: Microstrip Line (Rathod, 2020)

The majority of the electric field lines are found in the substrate, with the exception of a few that extend into the air. As a result, this transmission line cannot support a pure transverse electric- magnetic (TEM) mode of transmission due to the differing phase velocities in the air and the substrate. Instead, the quasi-TEM mode would serve as the primary mode of propagation (Rathod, 2020). As a result, in order to account for fringing and wave propagation in the line, an effective dielectric constant must be derived.

2.5.2. Cavity Model

The transmission line model described in the previous section is straightforward to use, but it has a number of flaws. Because it ignores field discrepancies at the radiating boundaries, it's particularly useful for rectangular design patches. To address these issues, the cavity model might be employed. This model depicts the internal component of the dielectric substrate as a cavity with electric walls on top and bottom. This assumption is based on the following observations for thin substrates (h):

In the region bordered by the patch metallization and the ground plane, the electric field is only z directed, and the magnetic field contains just the transverse components H_x and H_y . The electric walls at the top and bottom are based on this observation.

2.5.3. Full Wave Analysis

Full wave approaches are becoming more popular due to their rigor and precision. The Maxwell equation is solved in time domain using a Sommerfeld type integral equation. The finite difference time domain (FDTD) methodology, spectrum-domain integral equation analysis, and space-domain integral equation analysis are all popular numerical methods (Rathod, 2020). One

key assumption in the integral equation techniques is that the dielectric substrate and ground plane are both infinitely large. As a result, the solution becomes more exact when the substrate and ground plane are separated by many wavelengths. The FDTD technique is more efficient for finite-size antennas. Some of the most crucial aspects of Full Wave Analysis are as follows:

- ❖ Predicts Microstrip antenna properties at higher frequencies while also lowering the coefficient matrix and computation order.
- ❖ Calculates the resonant frequency, as well as the qualities and pattern of the radiation.
- ❖ It's versatile since it can be used on any antenna structure.
- ❖ It outperforms all other methods in terms of accuracy.
- ❖ Comprehensiveness, because it considers all sorts of losses.
- ❖ To reduce calculation costs, proper coding is essential because these are numerically intensive.

2.5.4. Finite Difference Time Domain

The most suitable numerical analytical method for patch antennas is FDTD. Any integrated semiconductor device in the antenna can be included in the analysis at the device-field interaction level, making FDTD extremely adaptable. As little more than a result, active antennas can be studied with precision. FDTD solves Maxwell's equations directly, without any analytical pre-processing, in contrast to other numerical approaches. As a result, practically any antenna geometry can be investigated. Due to the numerical nature of this technique, careful programming is required to keep computing costs to a minimum. In order to save computer resources, the domain for FDTD analysis of open region problems like antennas must be narrowed. Absorbing boundary conditions, such as analytical ABC or material ABC, are employed to truncate the antenna's physical domain.

As shown in figure 2.7, ABC, in the form of PML, can achieve a significant domain truncation with minimal reflection. The PML's design should be compatible with the antenna's FDTD technique. There are several flavors available in PML formulations. Split-field and non-split-field PM are the two types of PML. Non-split-field kinds are preferable since they are easier to code. The uniaxial PML formulation appears to be the most promising of the current PML

formulations. Computational error affects all FDTD algorithms, and the degree of error varies with the spatial and time step sizes used. Using numerical dispersion, the error is estimated.

Computational error affects most FDTD approaches, and the degree of error varies with the spatial and time step sizes used. Using numerical dispersion, the error is estimated. One of several grid-based differential numerical modeling techniques is the FDTD methodology (finite difference methods). The time-dependent Maxwell's equations (in partial differential form) are decomposed by using central-difference approximations to the space and time partial derivatives.

The time-dependent Maxwell's equations (in part calculus of variations) were decomposed using central-difference approximations to the space and time partial derivatives. In software or hardware, the resulting finite-difference equations are leapfrogged solved: At one moment in time, the electric field vector components in a volume of space are solved, then the magnetic field vector components in the same spatial volume are solved, and so on, until the required transient or steady-state electromagnetic field behavior has fully evolved. Some of the most important traits are as follows:

- ❖ Because of its ease of implementation, FDTD is a widely used numerical method.
- ❖ It is not necessary to perform any analytical pre-processing or modeling.
- ❖ It can be used on any geometries of any shape.
- ❖ In the computational domain, E and H fields are calculated everywhere.
- ❖ Absorbing boundary conditions are used to simulate a computer environment with no bounds.
- ❖ The grid-based differential numerical modeling approach FDTD is a part of.
- ❖ CFL criterion must be met in both time and space steps.
- ❖ ABCs and specific absorbing materials such as PML are used to establish absorbing boundary conditions in order to make the computing domain finite.
- ❖ In a leapfrogging procedure, the E and H fields are moment or modified.

- ❖ Within the computational domain, users can specify materials at any time.

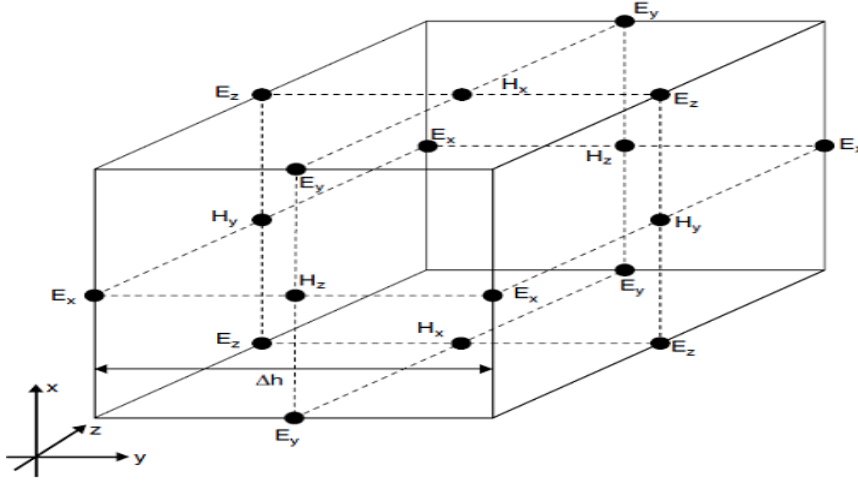


Figure 2.7: Geometry of Yee's cell used in FDTD analysis (Rathod, 2020)

2.6. Antenna Parameters

2.6.1. Radiation Pattern

A depiction of an antenna's far-field radiation characteristics as a function of the spatial coordinates given by the elevation angle and azimuth angle defines the antenna's radiation pattern. This pattern plot is created using spatial co-ordinates. Radiation intensity is defined as the ratio of power radiated to the unit solid angle. "Isotropic antenna" refers to an antenna that radiates evenly in all directions. The power density S is provided by equation 2.3 in any direction.

$$S = \frac{P}{4\pi r^2} \quad [2.3]$$

P is the total power radiated by the isotropic antenna, and r is the sphere's radius.

Equation 2.4 gives the radiation intensity for an isotropic antenna U_i .

$$U_i = r^2 S = \frac{P}{4\pi} \quad [2.4]$$

Despite the challenges of achieving an isotropic antenna, it is used as a benchmark. Effective antennas are directional, implying they emit more power in certain directions and less power in others. An unidirectional antenna's radiation pattern is constant in the H-plane, which is the E-

plane, but it changes in the orthogonal plane. Figure 2.8 shows the radiation pattern of a directional antenna.

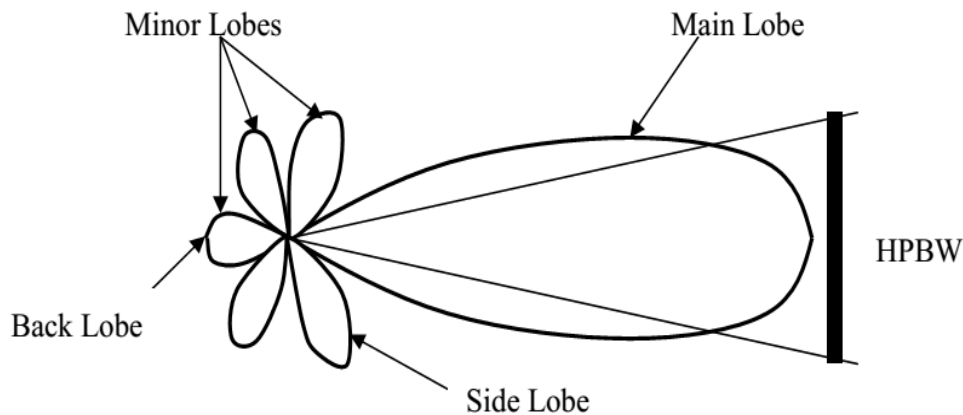


Figure 2.8: Radiation Pattern

Figure 2.8 shows that the half power beam width is the angle subtended by the half power of the lobe where we have maximum radiation.

- ❖ The Main Lobe is the one with the most powerful radiation.
- ❖ Minor lobes are lobes that exist alongside the principal lobe and emit undesirable radiation.
- ❖ Back lobe refers to the minor lobe that is exactly opposite the major lobe.
- ❖ The largest of the minor lobes, side lobes are found near the main lobe.
- ❖ Minor lobes are undesirable in most wireless systems; hence an effective antenna design should keep the number of minor lobes to a bare minimum.

2.6.2. Directivity

Directivity is defined as the ratio of the antenna's radiation intensity in a particular way to the mean radiation intensity in all directions. Directivity is defined as the ratio of an omnidirectional source's radiation intensity toward a specific direction or position to that of an isotropic source. Directivity is calculated using Equation 2.5.

$$D = \frac{4\pi U}{p} = \frac{U}{U_i} \quad [2.5]$$

Where D means the directivity of an antenna, P denotes the power emitted, U_i denotes the radiation intensity of an isotropic source, and U denotes the radiation intensity of an antenna. Equation 2.6 can be used to calculate maximum intensity if the direction of highest intensity is known.

$$D_{max} = \frac{U_{max}}{U_i} = \frac{4\pi U_{max}}{p} \quad [2.6]$$

D_{max} is an antenna's greatest directivity, and U_{max} is the antenna's maximum radiation intensity. An antenna's directivity is not affected by its direction because it is the ratio of two intensities of a given radiation. The decibel scale is used to express the degree of directivity (dB). The radiation pattern can be used to determine an antenna's directivity. An antenna with a thin main lobe has higher directivity and is hence more directive than one with a broad main lobe.

2.6.3. Input Impedance

According to (*Balanis C.A.*) , input impedance is the impedance of an antenna at its terminals, or the ratio of voltage to current at the pair of terminals. The ratio of the relevant components of the electric and magnetic fields at a point is known as input impedance. The input impedance is calculated using equation 2.7.

$$Z_{in} = R_{in} + j X_{in} \quad [2.7]$$

The antenna input impedance is Z_{in} , the antenna resistance is R_{in} , and the antenna reactance is X_{in} . The near-field power stored in the antenna is represented by X_{in} , which is the imaginary component of the impedance. The resistive component of the input resistance, made up of loss and radiation resistance is denoted by R_{in} . The power squandered in the loss resistance is lost as heat in the antenna due to dielectric or conducting losses, whereas the power connected with the radiation resistance is broadcasted by the antenna.

2.6.4. Voltage Standing Wave Ratio (VSWR)

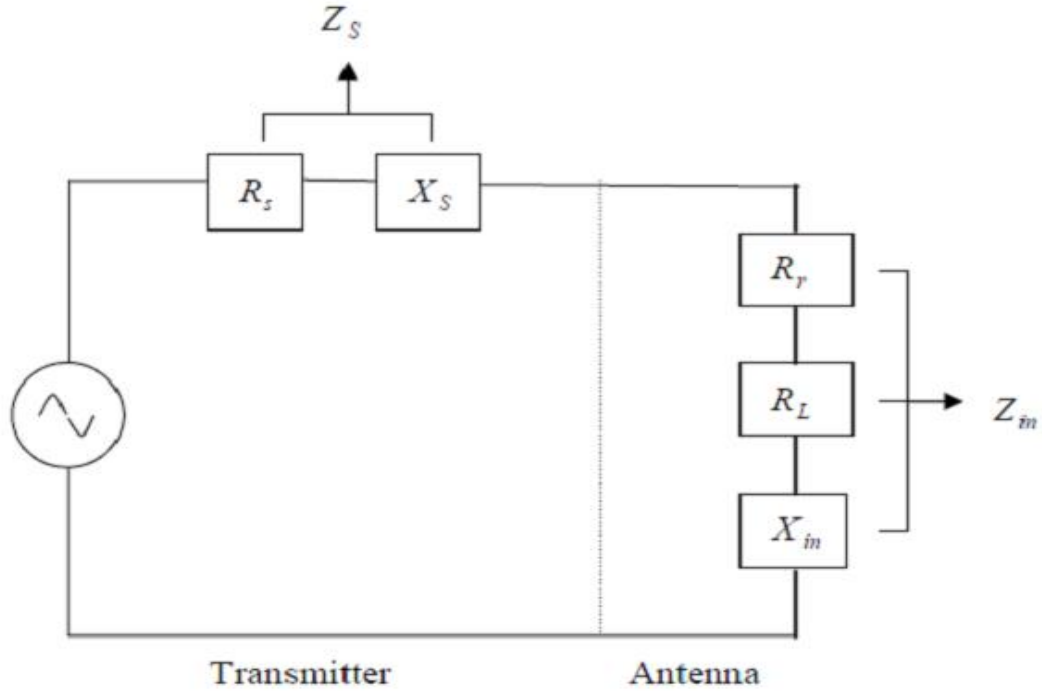


Figure 2.9: Transmitting Antenna Circuit (Rathod, 2020)

A high-flow of electricity between the antenna and the transmitter is required for an efficient antenna. More power may be transmitted when the antenna and transmitter impedances are well matched. The highest power is supplied when the transmitter impedance is equal to the complex conjugate of the antenna impedance. Equation 2.8 expresses the condition.

$$Z_{in} = Z_s^* \quad [2.8]$$

Where $Z_{in} = R_{in} + jX_{in}$ and $Z_s^* = R_s + jX_s$

Standing waves are created when electricity is reflected because of a mismatch. Standing waves are defined by a voltage standing voltage wave ratio (VSWR). In equation 2.9, determines the VSWR.

$$VSWR = \frac{1+\Gamma}{1-\Gamma} \quad (2.9)$$

Where Γ is the reflection coefficient, V_r is the amplitude of the reflected wave, and V_i is the amplitude of the incident wave. The impedance mismatch between the antenna and the

transmitter is measured by VSWR. When the VSWR is high, it indicates that there is a lot of mismatch, and when it is unity, it indicates that there is no mismatch at all. In order to radiate and transmit successfully, a functioning antenna's VSWR must be less than 2.

2.6.5. Return Loss

This is a measure of how often power is wasted towards the load since no power is returned as reflected. When the antenna and transmitter are out of phase, the reflected wave generates a standing wave. The return loss is a metric that indicates how well the antenna and transmitter are matched. The RL is expressed using Equation 2.10.

$$RL(dB) = -20 \log_{10} \Gamma \quad (2.10)$$

The RL = infinity when the reflection coefficient is 0, indicating that no power is returned or reflected. The VSWR of 2 is allowed for an antenna to function effectively because it produces a return loss of -9.54 dB, as stated.

2.6.6. Antenna Efficiency

Antenna performance is a metric which takes into account both the terminal losses and the directional antennas structure. The efficiency factor takes into account mismatch-induced wave reflection, as well as dielectric and conduction losses. The total antenna efficiency is calculated using Equation 2.11.

$$e_t = e_d e_c e_r \quad [2.11]$$

Conduction efficiency is equal to e_c , reflection efficiency is equal to e_r , and dielectric efficiency is equal to e_d . The antenna radiation efficiency e_{cd} is the consequence of combining conduction and reflection efficiency. It is defined as the ratio of radiation resistance R_r to power transmitted to R_L and R_r and may be represented using the equation 2.12.

$$e_{cd} = e_d e_c = \frac{R_r}{R_r + R_L} \quad [2.12]$$

2.6.7. Antenna Gain

Gain of the antenna and antenna quality factor were inversely proportional. Directivity is defined as an antenna's capacity to radiate energy in a preferred direction relative to other directions. Because the gain is equal to the antenna's directivity, an isotropic radiator's efficiency

is 100 percent. All antennas produce more radiation in some directions than others. Equation 2.13 gives the gain of an antenna.

$$\mathbf{G}(\theta, \phi) = e_{cd} \mathbf{D}(\theta, \phi) \quad [2.13]$$

2.6.8. Polarization

Polarization describes the direction of an electromagnetic wave over time and is proportional to the magnitude of the electric field vector. Polarization of the field vector is another name for antenna polarization. Polarization can be divided into two types: linear and circular (Bansal, 2008). Linear polarization can be seen in Figure 2.10.

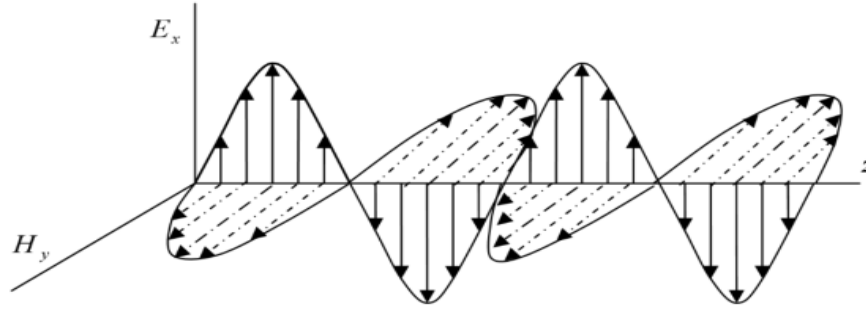


Figure 2.10: Linearly Polarized Wave (Rathod, 2020)

A forward and backward path along a line is taken by an electric field vector that is linearly polarized. When a signal becomes circularly polarized, the electric field vector rotates in a circular direction while the length remains constant. The wave is right hand circular polarized if the motion is clockwise, and left hand circular polarized if the motion is proportional to the applied force, as shown in figure 2.11.

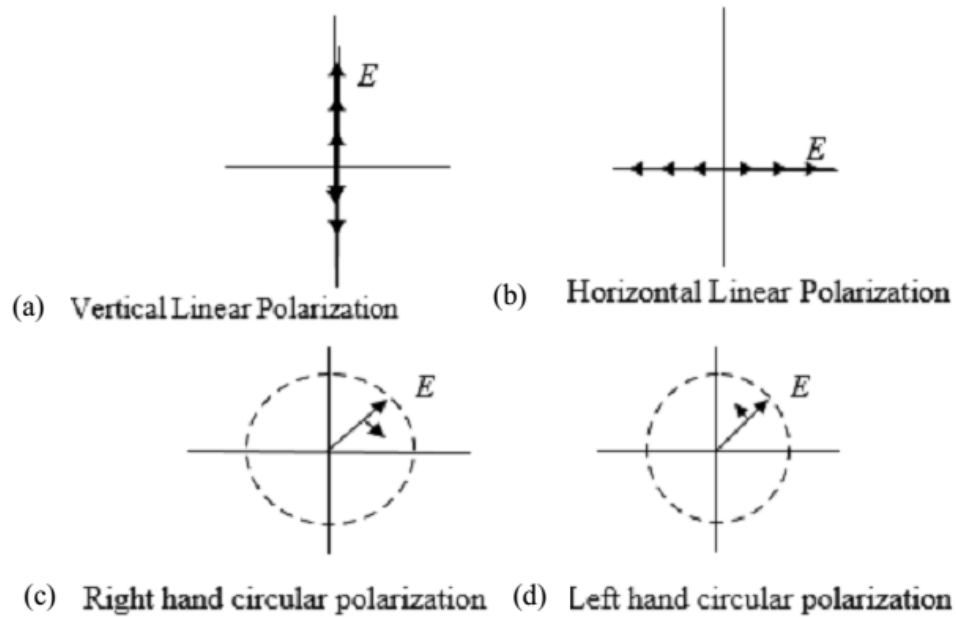


Figure 2.11: Polarization Schemes (Rathod, 2020)

2.6.9. Bandwidth

This is the frequency range whereby an antenna can effectively transduce electromagnetic waves. The bandwidth refers to the frequency range on each side of the resonance frequency in which the radiation pattern, input impedance, polarization, beam width, and gain values are all the same as the resonant frequency. The voltage standing wave ratio is used to determine an antenna's efficiency. An antenna with a VSWR of 2 or less can perform well because the return loss is somewhere around -9.54 dB.

2.7. Beam Forming

The technique of beam formation uses an array of antennas to convey radio waves in a certain direction. Rather than broadcasting energy/signals in all directions, beam forming antenna arrays detect the direction of interest and send/receive a larger beam of signals in that direction. This technology is widely used in radars and sonar, as well as in medical and communications applications, including 5G, where extremely high data rates are necessary and beam forming is the only way to achieve them. The signal is supplied to each antenna element individually in this technique. The phase and amplitude of each signal are then merged both constructively and destructively, concentrating the energy into a narrow beam or lobe(Rappa Port Wireless Communications.).

2.8. Applications of PIFA

The following are the application of PIFA:

- a) Planar Inverted F-Antenna for Handheld Devices
- b) Planar Inverted F-Antenna array for MIMO application
- c) Planar Inverted F-Antenna for Medical Applications

2.9 MIMO Systems

MIMO is an acronym that means Multiple-Input Multiple-Output. In fact, several transmitters and receivers can be used at each end of the radio link in order to achieve a high capacity. Multiple-input multiple output (MIMO) is a particular type of space and/or polarization diversity in which both the transmitter and receiver may use multiple antennas. MIMO -is a method for the coordinated use of several radio antennas in wireless network communications. The standard is common in home broadband routers(Khalid et al., 2020). The signal multiplexing is used for MIMO between multiple transmitting antennas (space multiplex) and frequency or time. This technology uses the OFDM for the channel access. The signal transmitted by m antennas is received by n antennas. Processing of the received signals may deliver several performance improvements in terms of range, quality of received signal and spectrum efficiency. In principle, MIMO is more efficient when many multiple path signals are received, as shown the 802.11n standard, the theoretical speed upper than 600 Mbit/s. However, the performance in cellular deployments is still subject to research and simulations. Moreover, it is generally admitted that the gain in spectrum efficiency is directly related to the minimum number of antennas in the link. Figure 2.12, shown various MIMO configurations, for example:

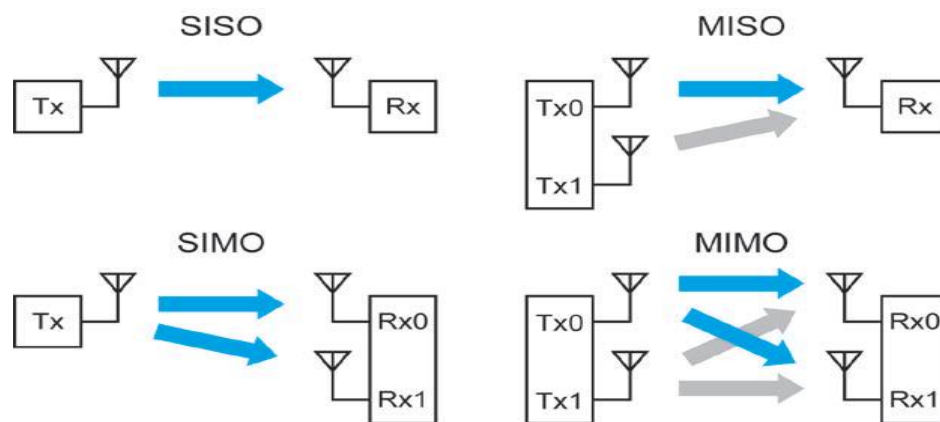


Figure 2.12: Radio access channel, variations of MIMO

- MIMO: Several antennas are placed at the transmitter and receiver.
- MISO: Several antennas are placed in the transmitter but only one in the receiver.
- SIMO: Only one antenna is placed in the transmitter and several are located in the receiver.
- SISO: Only one antenna is placed in both the transmitter and the receiver.

The main requirement for MIMO systems is that the antennas must be able to receive different signals, even though if they are closely spaced. The different signal paths should be uncorrelated to ensure a good diversity gain and the mutual coupling has to be as less as possible to avoid the energy transfer between antennas and therefore, the increase of the correlation.

Due to this requirements, implement MIMO systems in mobile phone is nowadays still a challenge, because it is difficult to add multiple antennas on something so small and pretend to have a good isolation. Another feature is that the performance of the antenna will be degraded by the effects of inter-antenna coupling, envelope cross-correlation and coupling to biological tissues in the user's hands.

Some advantages of MIMO technology are:

Array gain, that increase in received SNR (Signal Noise Rate), like a results from a coherent combining effect of the wireless signals at a receiver. The coherent combining could be realized through spatial processing at the receive antenna and/or spatial pre-processing at the transmit antenna.

Spatial diversity gain that mitigates fading and it is realized by providing the receiver with multiple transmitted signals in space, frequency or time. With an increasing number of independent multiple copies of the same signal, the probability that at least one of the copies is not experiencing a deep fade increases, then improving the quality and reliability of reception.

Spatial multiplexing gain, that offers a linear increasing in data rate, transmitting multiple and independent data streams within the bandwidth of operation. Moreover, the spatial multiplexing gain increases the capacity of a wireless network.

Interference reduction, that in general results from multiple users sharing time and frequency resources. This kind of interference may be mitigated by exploiting the spatial dimension to increase the separation between users. Furthermore, the spatial dimension can be leveraged for the purposes of interference avoidance minimizing interference to other users. Interference reduction and avoidance improve range and coverage of a wireless network.

In general, it may not be possible to reach simultaneously all the benefits described because of conflicting demands on the spatial degrees of freedom. Nevertheless, the usage of some combination of this across a wireless network could be to improve capacity, reliability, and coverage.

2.9.1. MIMO in Cellular Networks

MIMO technology is used in other kinds of wireless networks for example, in cell networks (4G and 5G technology) in several forms:

1. Network MIMO or cooperative MIMO: Coordinates signaling among multiple base stations. Used for 4G LTE.
2. Massive MIMO: Uses large numbers (hundreds) of antennas at a base station, basically for 5G.
3. Millimeter Wave MIMO: Uses high-frequency bands where spectrum availability is larger than on bands licensed for use on 5G and beyond.

2.10. Cellular Radio Communication System

The cellular concept is to partition a geographical area into “cells”, each covering a small fraction of a city. Each cell is allocated a “channel group”, i.e., a subset of the total list of channels. A second cell, distant from a first cell using a particular channel group, can reuse the same channel group. This is called “frequency reuse”(Patwari, 2011). This assumes that at a long distance, the signals transmitted in the first cell are too low by the time they reach the second cell to significantly interfere with the use of those channels in the second cell. There are dramatic technical implications of the cellular concept. First, rather than one base station, you need dozens or hundreds, deployed across a city. Both of these are actually enabled by semiconductor technology advancement, which made the base stations and the automated wired PSTN cheaper (Patwari, 2011).

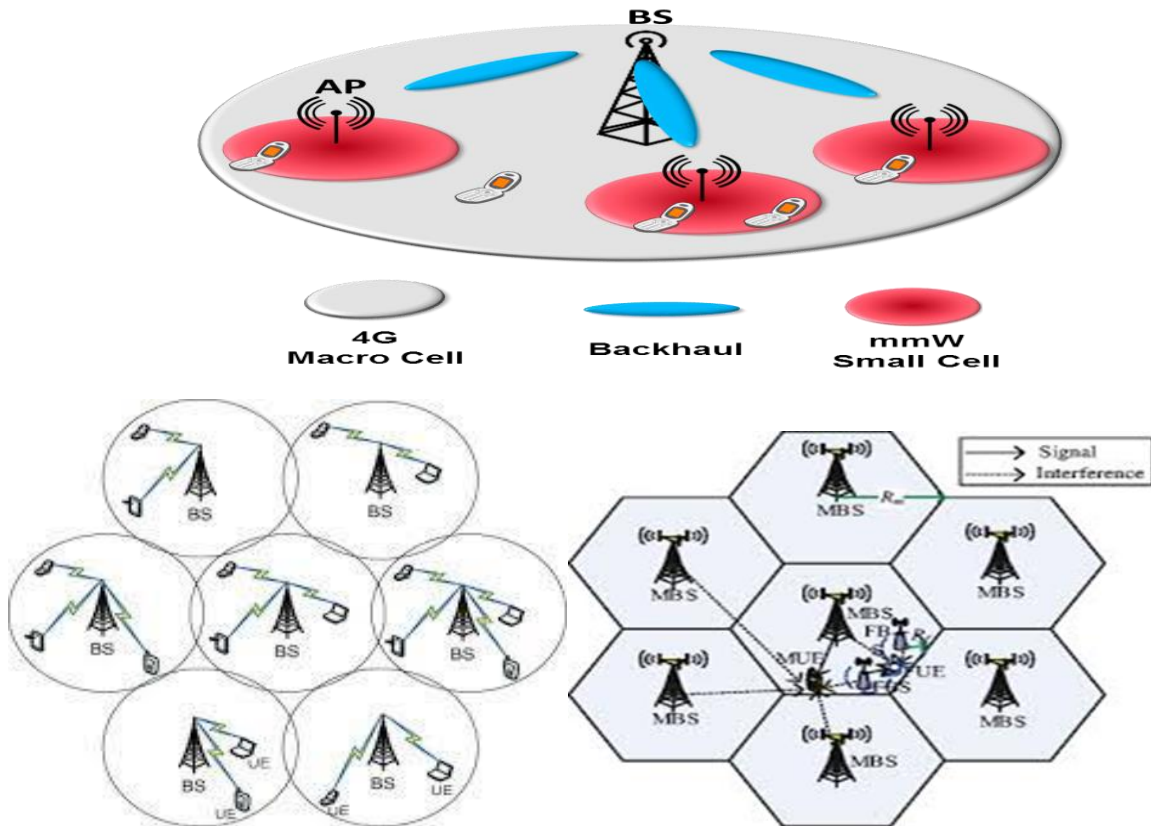
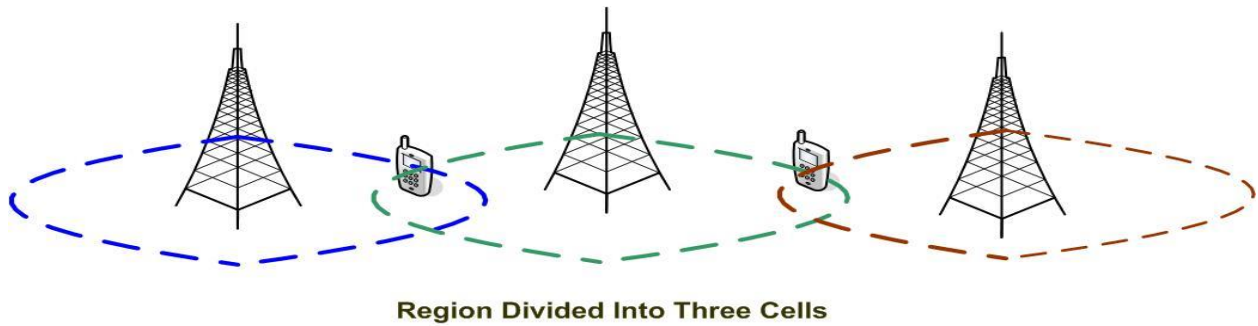


Figure 2.13: Cellular network with Sectorial antenna (Patwari, 2011)

2.11. Importance of mmWave

Millimetre-wave (mmWave) technology for the 60-GHz band (Negi, 2016) is among the most interesting prospects potential circuit, antenna, and communication system innovators in the future decade. A new era of expanding communication systems begins at V-band (60 GHz), offering uncompressed increasing media exchanges, sensing and radar applications, and near-instantaneous access to massive data libraries at speeds of several tens of gigabits per second. Due to consumer demand for these applications, millions of 60-GHz communication devices would be made and marketed in the future.

V-band (60 GHz) communication is suitable for gigabit wireless data transfer over short distances because of these characteristics. Skin and closeness effects, material losses, and reaching the top dispersal study at frequency components ranging from 60 GHz to hundreds of GHz shows that wireless connections would be needed in the near future, in addition to providing vast capacity for future WPANs and WLANs. The following are some of the most essential characteristics of V-band (60GHz): The 60-GHz millimeter-wave (55-65GHz) spectrum can be used without a license all around the world. Path loss is present, and it is employed for short-range applications.

- ❖ It has a dense frequency reuse pattern and high data speeds of roughly 25Gbps.
- ❖ Higher frequency leads to reduced component sizes.
- ❖ It makes use of antennas with a high gain and a large coverage area.
- ❖ The mmWave band has a large spectrum capacity, a small antenna configuration, and can transmit more data than any other antenna.
- ❖ It also has 20 times the bandwidth of any other antenna.
- ❖ Signals are muffled due to oxygen absorption, giving interference immunity and superior security.
- ❖ mmWave wave's travel exclusively by line of sight, is stopped by building walls, and is attenuated.
- ❖ They are used in dense populations, radio astronomy, microwave, and VANET. A large spectrum of 7GHz is available.
- ❖ mmWave waves travel purely by line of sight, are barred by building walls, and are attenuated.
- ❖ It belongs to the millimeter wave V-band.
- ❖ It operates in the V-band of the millimeter wave band, which runs from 50 to 75 GHz, and has a weak penetration problem.

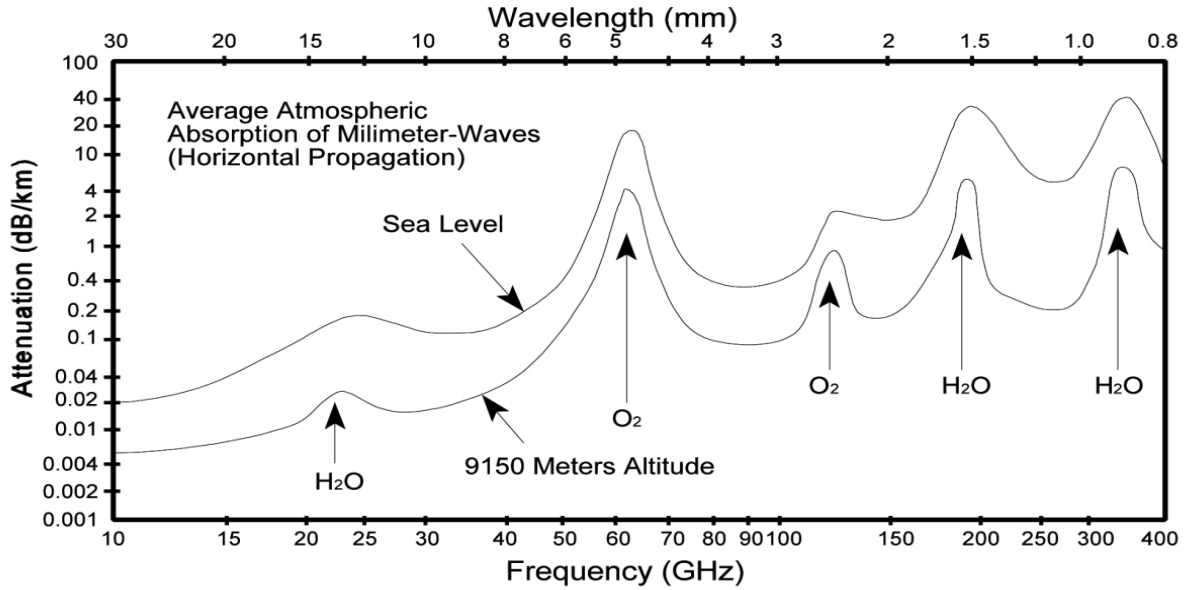


Figure 2.14: Atomic and environmental penetration at millimetre waves (Sandi et al., 2020)

2.12. Examining Relevant Literature

In the form of study papers, numerous academics have examined and published their findings on a variety of antenna variables such as radiation characteristics, impedance bandwidth enhancement, gain, enhancing radiation pattern, compactness, and polarization of PIFA MSAs. It was extremely useful in understanding how to improve the aforementioned antenna properties. The presents a summary of research on microstrip patches and PIFA antennas that has been published.

The PIFA antenna design for satellite applications is the focus of the paper (Thu et al., 2020). The study's main goal is to answer the research problem of locating a simple and compact design for tiny satellite applications in the actual world. For low Earth orbit (LEO) applications in the S band, a Planar Inverted-F Antenna (PIFA) with two heights of 12mm and 10mm is proposed. The antenna is a single-form antenna that is fed by a coaxial probe. The antennas have a high return loss efficiency of -18.426dB and a return loss bandwidth of 471MHz. The results of the radiation pattern analysis are based on a beam width angle of 85.1°. Furthermore, the absolute E-filed radiation effect and the peak directivity gain result of 4.7dBi are reported.

In the publication Microstrip Array Antenna with Ultra-Wideband for 5G Millimeter-wave (Sandi et al., 2020), the authors outline the usage and offer a design for a 5G millimeter-wave ultra-wideband microstrip array antenna that uses a stepped line cut and U-slot combination. In

order to improve bandwidth performance, the suggested design uses a proximity coupling feeding mechanism. The patch antennas bandwidth performance is compared to a standard antenna array design to evaluate the bandwidth enhancement. Numerical and modeling findings show a significant increase in bandwidth performance when compared to standard designs. With a bandwidth of 4.47 GHz and a gain of 8.71dB, the proposed antenna may operate in the 28 GHz frequency spectrum. These findings show that the proposed antenna design is suitable for millimeter-wave 5G applications.

Microstrip antennas are frequently employed in paper (Journal, 2020), because they are small and easy to obtain a unidirectional radiation pattern. Microstrip antennas, on the other hand, have a limited bandwidth, which limits their use in wideband systems. This study proposes a simple compact wideband patch antenna with rectangular slot, consisting of a rectangular patch trimmed from a microstrip feeding structure and a truncated ground plane. On a 35mm x 28mm x 1.6mm FR4 printed circuit board, the suggested antenna is etched. The settings are fine-tuned using ADS simulation software. A low return loss of -18dB was achieved at a resonant frequency of 6.8 GHz. The antenna has a directivity of 5.17dBi and a gain of 0.085dBi.

A compact tapered slot antenna array for 5G millimeter wave massive MIMO system has been presented. The system has a good beam-forming performance because the space between array elements meets the requirement of half wavelength. The operation band of antenna array is from 22.5 GHz to 32 GHz. The S11 is -10 dB along the operation band and the deep value of it is about -35 dB which is from 25 GHz to 30 GHz. In this paper, the antenna size is about 6 cm and it cannot be used for mobile handset(Yang et al., 2017).

The single band PIFA antenna has been presented. It has three rectangular shape elements located at the same line and separated by an equal distance between their centers. The antenna serves 28 GHz frequency and its S11 is -25 dB at this frequency. The peak gain of it is 6.06 dBi. This designed is served single band only and array structure has not be used. The proposed antenna design in this thesis uses the array structure and serves dual bands (Haraz et al., 2015).

An eight port dual polarized MIMO antenna for 5G Smartphone applications has been presented. The operation band is (2.55 GHz-2.65 GHz). The antenna has a simple structure where the single elements of it has a square shape hollow from inside and the boarder width

equal to 2mm. Its S_{11} is -35 dB at 2.6 GHz. In this paper, only a single element antenna has been designed and it also does not support higher 5G frequencies (28 GHz) (Li et al., 2017).

5G massive MIMO antenna system for a triangular 72- port base station with switched beam steering future. The base station dimensions are 120x60 cm. Every single port consists from 2x2-patch antenna array. The antenna consists from three metallic layers, the top one has the patches, the middle one is the ground layer and the bottom one has the feeding networks. The probe feed techniques used in the design (Al-Tarifi et al., 2018).

This study differed from the previous research in that it was conducted using CAD-FEKO simulation software at the mmWave frequency band for cellular radio communication applications, with changes to various parameters such as plate width, ground plane width, ground plane length, patch width, patch length, and height. The characteristics of single, four-by-one, and four-by-four elements of a planar inverted F-antenna were analyzed using different parameters, and the results were compared using the above-mentioned design parameters. In all the literatures seen so far in above Section, different PIFA antenna design and modeling has been investigated at different design parameters. However, the contributions of this thesis work are underlined in the following points.

In this thesis, with a change of different parameters each design has also recommended for mmWave MIMO cellular radio communication application. This is also another major contribution of this thesis work. Simulation results were also discussed in form of table in the following result and discussion section.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Introduction

Considering the application to be achieved and parameter requirements is the first step in the antenna design phase. The significance of frequency cannot be emphasized. Further, the directional antennas mode of operation would be considered, and the substrate to be employed would be established. The antenna's size and shape are computed after all of the data has indeed been decided.

In the preceding part, designers described PIFA antennas applications, as well as recent wireless communication applications such as radar, cellular radio, microwave, and space communication. It's vital for a mobile cellular handset application to be as familiar as possible. For base station antennas, other traditional patch antennas are employed. Furthermore, this PIFA antenna is suitable to be used as a cellular mobile communications base station antenna.

CAD-FEKO, Win-prop, and Matlab2016a are among the common software used in proposed antenna for analytical modeling and patch design. Matlab can be used to study statistics, enhance algorithms, and establish best practices and packages. Matlab would be used for analytical modeling in this research. CAD-FEKO, Win-prop is a tool that allows you to design, evaluate, and optimize high-performance electromagnetic (EM) components and systems. It offers a fast and efficient solution for high frequency (HF) devices including such antennae, analyzers, and connectors. Time and Frequencies Domain the CAD-FEKO Winprop programmer provides domain solvers as well as supplementary solver modules for particular applications and cellular coverage density investigation.

3.2 Materials

Selecting of such a dielectric substrate material is the beginning stages inside the design process. More than element, substrate conditions like thickness and permittivity govern the dominant characteristic of a PIFA array. Since weight has become an important factor in cellular systems, a substrate which not only has excellent dielectric properties but it is also relatively thin should be chosen (Loharia & Rana, 2016).

The dielectric constant and loss tangent were the most important factors in choosing the substrate. A high dielectric constant resulted in a smaller patch size; however this reduced bandwidth efficiency and made constructing a very small patch size antenna problematic. The antenna's efficiency was being harmed by a high loss tangent. Since FR-4 has a moderate dielectric constant (Adhikari et al., 2021), loss tangent, and is comparatively cheap, materials were selected for this study.

3.3 Methodology and Work Flow Model

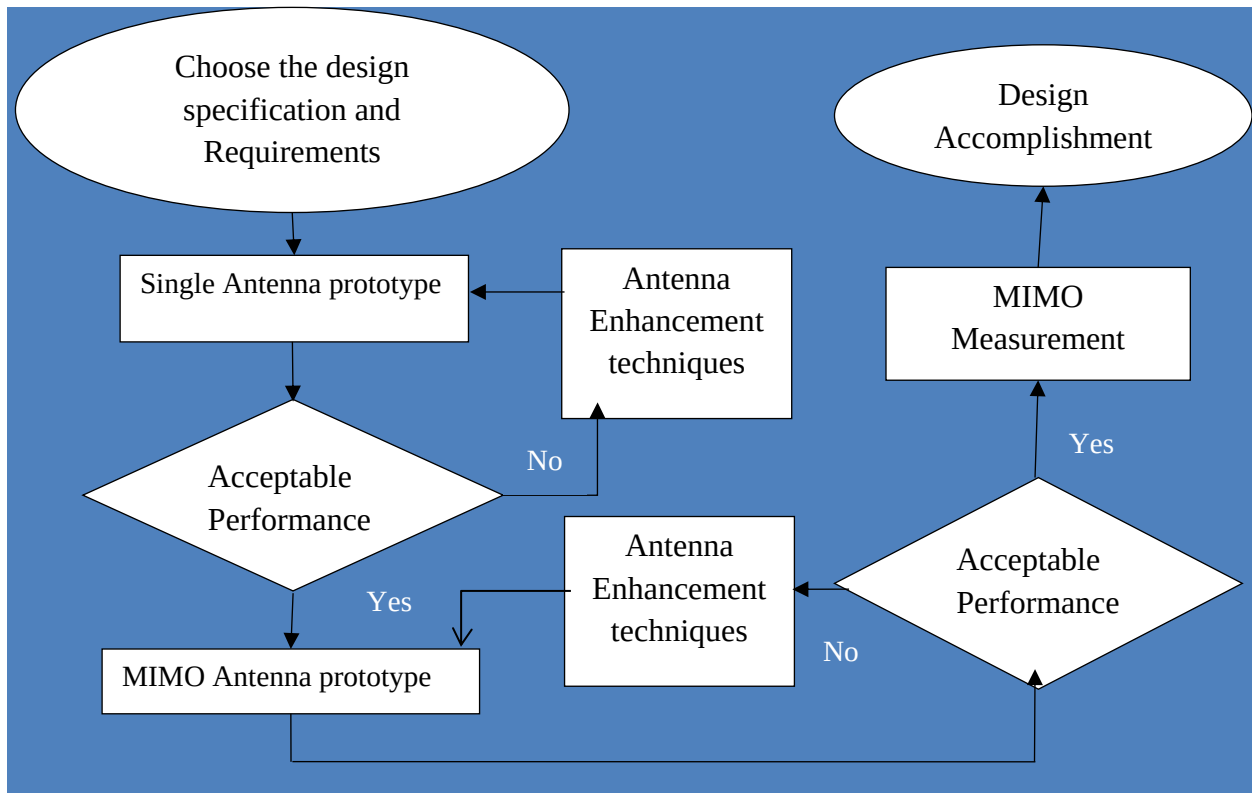


Figure 3.1: Flow Chart of design Methodology

The figure 3.1 shows the methodology and work flow charts of the thesis. First researcher was determined the design specification and the requirements. After that, the single PIFA antenna would be design and investigated improvement of performance. If the performance of the designed antenna had best performance, extend the array configuration to 1x4 elements. If the performance was not improved, antenna enhancing techniques applied to improve the performance of the proposed design. To improve the return loss of the proposed the matching point calculation and design calculation was done. The coupling of the array was one of the issues for MIMO antenna. Mutually coupling among closely spaced radiating elements is

essential for the performance of microstrip antenna systems due to fact that induced currents, input impedance and radiation patterns are affected when antenna elements are correlated which in turn reduces capacity of MIMO system and the techniques that can take in this work to reduce correlation is through physically separating radiating elements by distance $d = 3\lambda/2$. However this solution is impractical in hand held wireless devices considering space limitation constraints.

Mutual coupling is a critical issue in antenna elements is placed in the form of array between the antenna elements. In this proposed work the ground plane is set to be infinite in FEKO. This is also the case with the following two antennas. To model a probe-fed PIFA antenna with infinite ground plane in FEKO, one should create a planar multilayer substrate and set a ground plane with space between the elements. Then create wire probes between patches and ground plane. Create a wire port at the bottom end of feeding probe. The mesh size is Fine. The radius of the wire probe (wire segment radius) is set to be 0.5mm.

3.4 PIFA Design Calculation

The following are the three major important parameters to consideration in design of PIFA antenna:

- Frequency of Operation (f_r): the antenna's resonant frequency must be carefully considered.
- Substrate Dielectric Constant (ϵ_r): The dielectric material used in this design has a dielectric constant of 4.4.
- Height of dielectric material (h): It is critical that now the antenna is just not large in it to be designed as a PIFA or other comparable antenna. As a result, the dielectric substrate selected now has a thickness of 0.1 mm.

$$L_p = -W_p + W_s + \frac{\lambda}{4} + h \quad (3.1)$$

Where λ is the guide wavelength in the dielectric. For special cases, above equation(3.1) is

$$\text{reduced to: } L_p = \frac{\lambda}{4} + h, \text{ for } W_p = W_s \quad (3.2)$$

$$\text{and } L_p \approx -W_s + \frac{\lambda}{4} + h \text{ for } W_s \approx 0 \quad (3.3)$$

Then from above equation the resonant frequency can be expressed as:

$$f = \frac{c}{4(Lp + Wp - Ws - h)\sqrt{\epsilon_{reff}}} \quad (3.4)$$

$$\lambda_o = \frac{c}{f} \quad (3.5)$$

$$Wp = \frac{c}{2f} \sqrt{\frac{2}{\epsilon r + 1}} \quad (3.6)$$

$$Lp = Leff - 2\Delta L \quad (3.7)$$

$$Leff = \frac{c}{4f\sqrt{\epsilon_{reff}}} \quad (3.8)$$

$$\Delta L = 0.412h \frac{(\epsilon_{reff} + 0.3)(\frac{W_p}{h} + 0.264)}{(\epsilon_{reff} - 0.258)(\frac{W_p}{h} + 0.8)} \quad (3.9)$$

$$\epsilon_{reff} = \frac{\epsilon r + 1}{2} + \frac{\epsilon r - 1}{2} [1 + 12 \frac{h}{W_p}]^{\frac{-1}{2}} \quad (3.10)$$

$$Lg = Lp + 6h \quad (3.11)$$

$$Wg = Wp + 6h \quad (3.12)$$

$$\lambda = \frac{\lambda_o}{\sqrt{\epsilon_{reff}}} \quad (3.14)$$

Step 1, Calculation of the wave length (λ_o): from equation (3.5):

$$\lambda_o = \frac{c}{f} = 5.00 \text{ mm, Where } c = \text{Speed of light value } 3 \times 10^8 \text{ m/sec}$$

Step 2, Calculation of the width (W_p): the width is given by equation (3.6) as

$$Wp = \frac{c}{2f} \sqrt{\frac{2}{\epsilon r + 1}} = 1.52 \text{ mm}$$

Step 3, Calculation of effective dielectric constant: Where ϵ_{reff} = effective dielectric constant and the equation for it is given in (3.10)

$$\epsilon_{reff} = \frac{\epsilon r + 1}{2} + \frac{\epsilon r - 1}{2} [1 + 12 \frac{h}{W_p}]^{\frac{-1}{2}} = 3.456$$

Step 4, Calculation of the effective length (L_{eff}): from equation (3.8)

$$Leff = \frac{c}{4f\sqrt{\epsilon_{reff}}} = 0.7 \text{ mm}$$

Step 5, Calculation of the length extension (ΔL): equation (3.9) gives the length extension as

$$\Delta L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left(\frac{W}{h} + 0.8 \right)} = 0.047 \text{ mm}$$

Step 6, Calculation of the actual length of the patch (L): the actual length is obtained by subtracting the length extension from the effective length.

$$L_p = L_{\text{eff}} - 2\Delta L = 0.61 \text{ mm}$$

Step 7, Calculation of the ground plane dimensions (L_g and W_g): The transmission line model is applicable to infinite ground planes only. However, for practical considerations, it is essential to have a finite ground plane. Hence, for this design, the ground plane dimensions would be given as:

$$L_g = L_p + 6h = 0.631 + 6(0.1) = 1.231 \text{ mm}$$

$$W_g = W_p + 6h = 1.52 + 6(0.1) = 2.12 \text{ mm}$$

L_g and W_g are length and width of ground plane and h is the thickness of the substrate given as 0.1mm.

Where, L_p = length of the patch,

λ = wavelength.

ϵ_r = dielectric constant

c = free space velocity of light 3×10^8 m/s

W_p = width of the patch

f = frequency of operation

3.5. Design Specifications for Single Element PIFA Antenna

The ground plane, radiating patch, and shortening plate are the basic components of PIFA, with shortening plate interconnecting the antennas patch and surface. It uses a basic structure supplied by input resistance 50 ohm coaxial feed between both the ground plane and the radiating patch, with the ground plane folding place at a single edge of the patch and length as indicated in Fig 3.2 below.

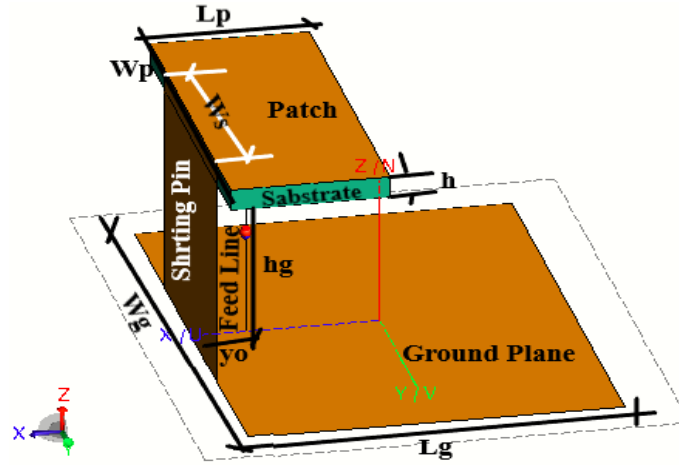


Figure 3.2: Single element PIFA patch antennas

Figure 3.2, illustrates a single element PIFA structure. The antenna was created on a thick FR-4 substrate generated by CAD-FEKO. The width and length of ground plane on bottom of the design. The antenna edge is d distance away from the feed probe. The PIFA has a width shorting strip added to that though. Table 3.1 summarizes the antennas design specifications of calculated and optimized value of the proposed design. The optimization of the parameters was done by using Altair HyperStudy Optimization software.

Table 3.1: The calculated and optimized physical dimensions of the proposed single Element PIFA Antenna

Parameters	Symbols	Calculated Value (mm)	Optimized value(mm)
Width of the Ground Plane	W_g	2.12	3.501
Length of the Ground Plane	L_g	1.231	1.657
Width of the Patch	W_p	1.52	1.53
Length of the Patch	L_p	0.631	0.76
Short plate width	W_s	1.23	1.01
Thickness of substrate	h	0.1	0.52
Feed position	y_o	0.22	0.31
Air Gap	h_g	1.0	0.97

The radiated power, on the other hand, is more concentrated in one direction. This really is owing to the single layer antenna's narrower beam width. The antenna element spacing and alignment could be used to evaluate the radiation characteristics of an antenna array. The antenna array's

emission pattern and gain are also influenced by the phase and amplitude variations among its segments. The beam formation adjustment is accomplished through electronic control of the phase and amplitude discrepancies. This means that the emitted energy can be directed in the direction of the receiver. Active surveillance of a mobile object is feasible because to electrical management of phase and amplitude discrepancies. The fundamental purpose behind using this type of antenna system for a man-machine interface is to achieve this.

The suggested beam-forming array is made up of four equal-sized but non-uniformly stimulated elements. The array factor (AF) is derived from isotropic point sources in this section. Isotropic point sources can be thought of as the perfect antenna, radiating power in every direction. The array factor is made up of point source orientation and spacing information, while the component element comprises the radiation feature of a specific antenna element.

Array Factor for N Elements

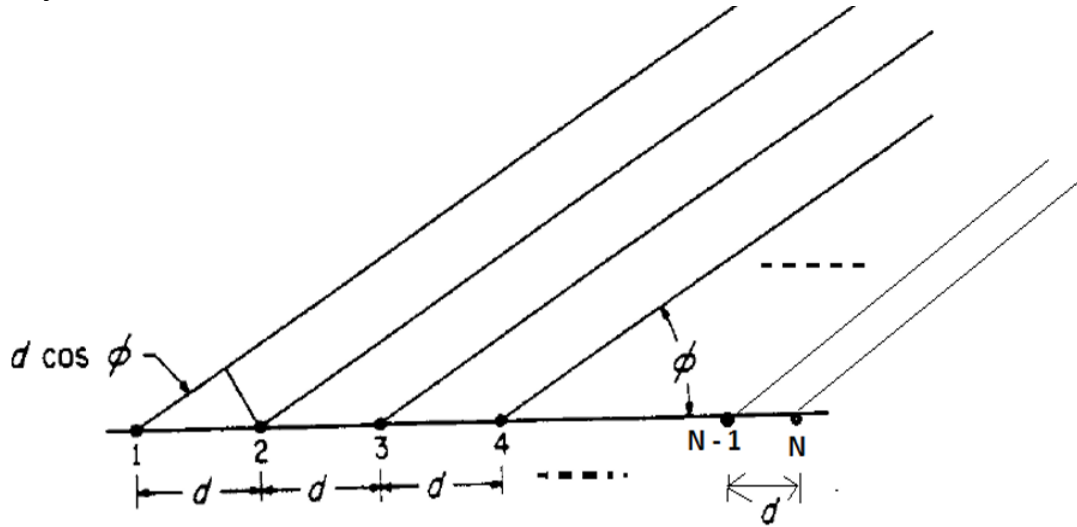
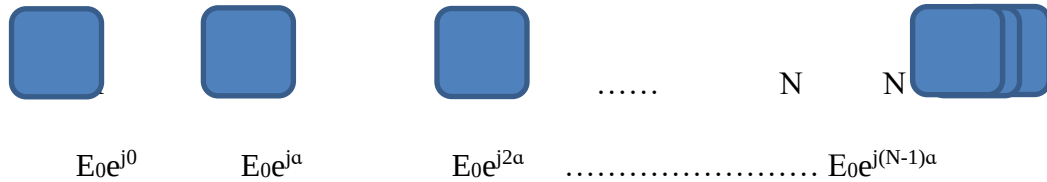


Figure 3.3: A linear array of non-directional radiators having N nodes



$$AF = E_0 e^{j0} + E_0 e^{j\psi} + \dots + E_0 e^{j(N-1)\psi} \quad (3.15)$$

$$\psi = \alpha + \beta d \cos \theta \quad (3.16)$$

$$\beta = \frac{2\pi}{\lambda} \quad \alpha = -\beta d \cos \theta \quad \theta = \cos^{-1} \left(\frac{\alpha}{-\beta d} \right) \quad d = \frac{3\lambda}{2}$$

The maximum radiation takes place at $\psi = 0$

From the above relation of the phase change can be calculated with respect to the steering angle:

Theta(θ)	$\alpha = -\beta d \cos \theta$
0°	$-(\frac{2\pi}{\lambda})(\frac{3\lambda}{2})\cos(0^\circ) = -3\pi * 180/\pi = -540^\circ$
30°	$-3\pi * \cos(30) * 180/\pi = -467.65^\circ$
60°	$-3\pi * \cos(60) * 180/\pi = -270^\circ$
90°	0°

$$\text{Amplitude Pattern: } |AF| = \left| \frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \right| \quad (3.17)$$

$$\text{Phase Pattern: } AF = \left| \frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \right| e^{j\frac{(N-1)\psi}{2}} \quad (3.18)$$

$$\text{Phase factor is } \frac{(N-1)\psi}{2}$$

Pattern Multiplication

$$\left\{ \sin \theta \frac{\sin\left(\frac{kW}{2} \cos \theta\right)}{\cos \theta} \right\} \cos\left(\frac{kL}{2} \sin \theta \sin \phi\right) \text{ Single PIFA for H-Plane} \quad (3.19)$$

$$\left\{ \frac{\sin\left(\frac{kh}{2} \cos \phi\right)}{\frac{kh}{2} \cos \phi} \right\} \cos\left(\frac{kL}{2} \sin \phi\right) \text{ Single PIFA for E-plane} \quad (3.20)$$

$$\text{Array Pattern} = AF \times (\text{pattern of Single PIFA antenna}) \quad (3.21)$$

Take a look at the array in Figure 3.3, which is obtaining a signal from a propagation direction that is incoming at an angle to the array's surface.

3.6. Design Specifications for 1x4 PIFA Antenna Array

Design Single element PIFA design is extended to be 1x4 as shown in figure 3.4 and table 3.2 shows dimensions of 1x4 antenna array. Referring to the calculation of the distance between the elements: that denoted as 'd' the distance between two elements. It depends on the wave length (λ). For this to reduce the coupling 1x4 planar PIFA, $d = 3\lambda/2$, since the value of L_p , $d \geq L_p$. Because, of to reduce the mutual coupling between the elements. That causes the antenna elements to radiate.

$$d = \frac{3\lambda}{2} = \frac{3 \times 5}{2} = 7.5 \text{ mm.}$$

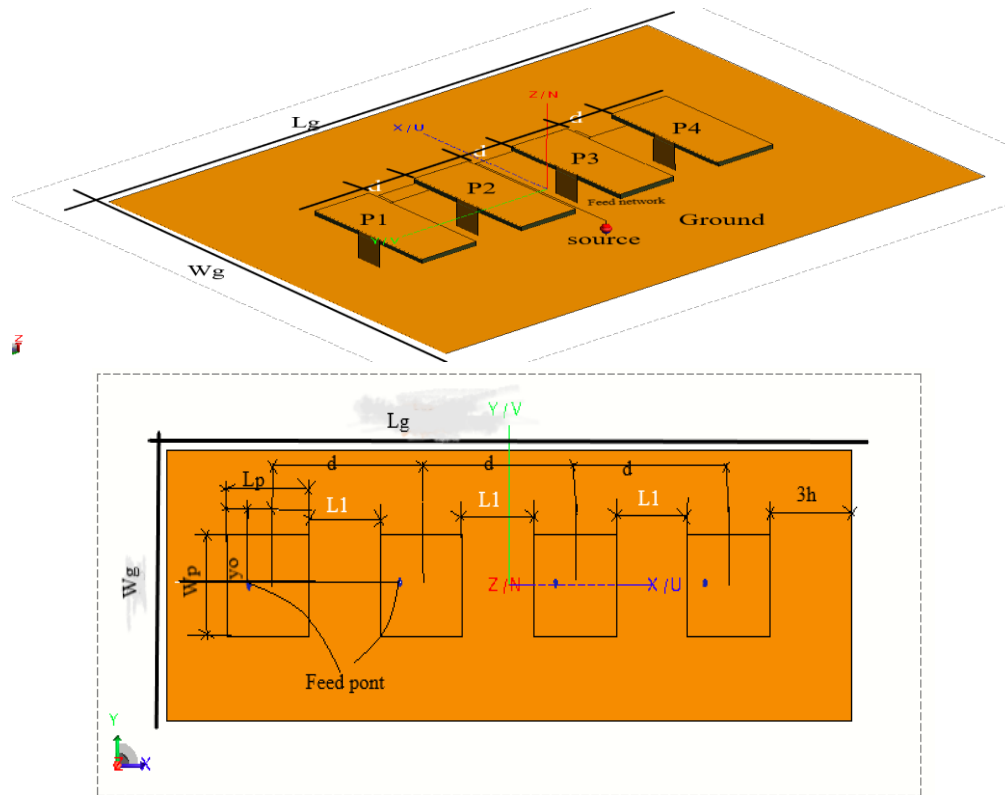


Figure 3.4: 1X4 PIFA antenna Array design model

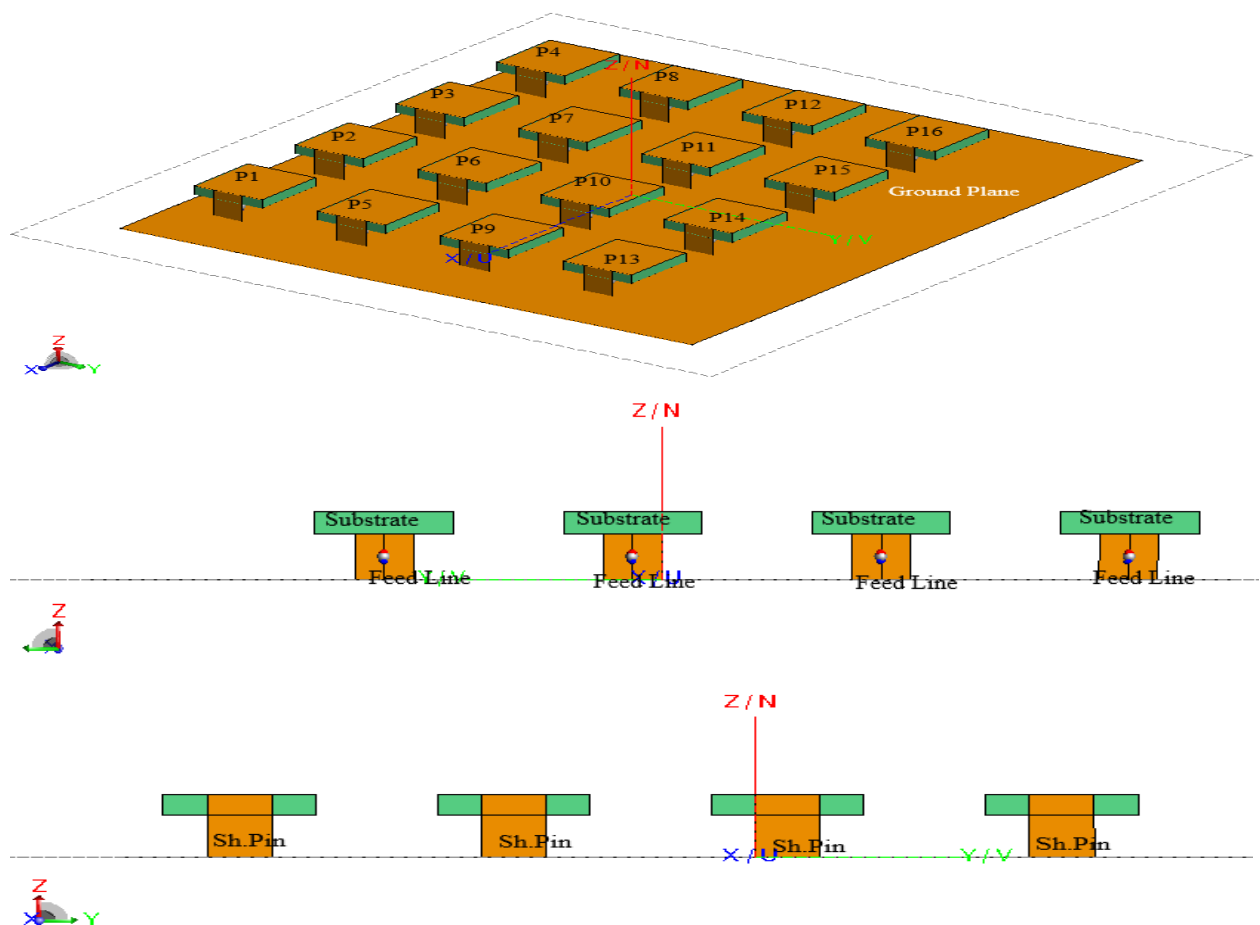
Table 3.2: The calculated and optimized physical dimensions of the proposed 1x4 PIFA Antenna Array

Parameters	Symbols	Calculated Value(mm)	Optimized value (mm)
Width of the Ground Plane	Wg	23.65	28.6
Length of the Ground Plane	Lg	2.12	3.00
Width of the Patch	Wp	1.52	1.42

Length of the Patch	L_p	0.631	1.02
Short plate width	W_s	1.0	0.98
Element Space	d	7.5	7.63
Thickness of substrate	h	0.1	0.32
Feed position	y_o	0.22	0.28
Air gap	h_g	1.0	0.87

3.7. Design Specifications for 4x4 Elements PIFA Antenna Array

Design 1x4 element PIFA Array antenna design is extended to be 4x4 as shown in figure 3.4 and table 3.3 shows dimensions of 4x4 array antennas. Referring to the calculation of the distance between the elements (d), this is $3/2$ of wavelength ($3\lambda/2$). The same producers of 4X1 PIFA were applied to design the appropriate geometry of the 4X4 PIFA array antenna. But the row of the single element was multiplied by the four to the y-axis. All parameters are specified below table 3.3.



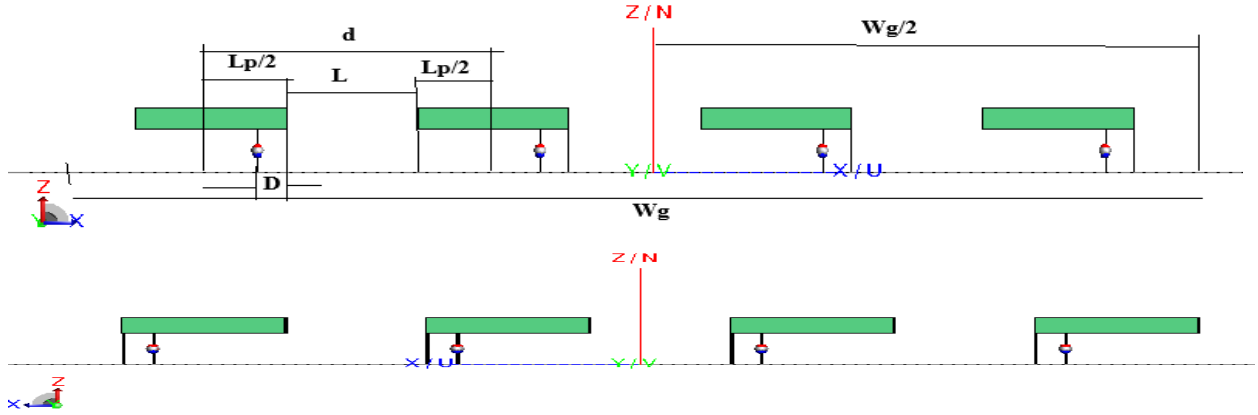


Figure 3.5: The design structure and dimensional specification of the 4X4 PIFA array antenna

Table 3.3: The calculated and optimized physical dimensions of the proposed 4x4 PIFA Antenna Array

Parameters	Symbols	Calculated Value(mm)	Optimized value(mm)
Width of the Ground Plane	W_g	23.44	26
Length of the Ground Plane	L_g	24.24	26.2
Width of the Patch	W_p	1.52	1.54
Length of the Patch	L_p	0.631	1.13
Short plate width	W_s	1.23	0.89
Distance between Elements	d	7.5	8.02
Thickness of substrate	h	0.1	0.4
Air gap	h_g	1.00	0.89
Feed point position	y_o	0.22	0.25

3.8. Feeding Techniques

The feed line is used to excite the antenna via radiation contact, either direct or indirect. Microstrip patch antennas can be made in a variety of ways, as detailed in the previous chapter. Because employing the coaxial feed method can boost bandwidth for PIFA and is a highly frequent technology used for feeding microstrip patch antennas, it was chosen for this thesis. The inner conductor of the coaxial connector is soldered to the radiating patch through the dielectric, while the outer conductor is attached to the ground plane. Antenna bandwidth can be enhanced in a variety of ways, including increasing the thickness of a substrate with a low dielectric constant, probe feeding, cutting slots, cutting notches, and using alternative antenna forms.

Coaxial feeding position calculation, consider the structure of the single PIFA, the calculation is done per the diagram shown with mathematical modelling (S. E Jasim, M. A. Jusoh, M. H. Mazwir & S. N. S. Mahmud).

Most microwave applications are designed with an input impedance of 50Ω , so matching the antenna to 50Ω is our desire.

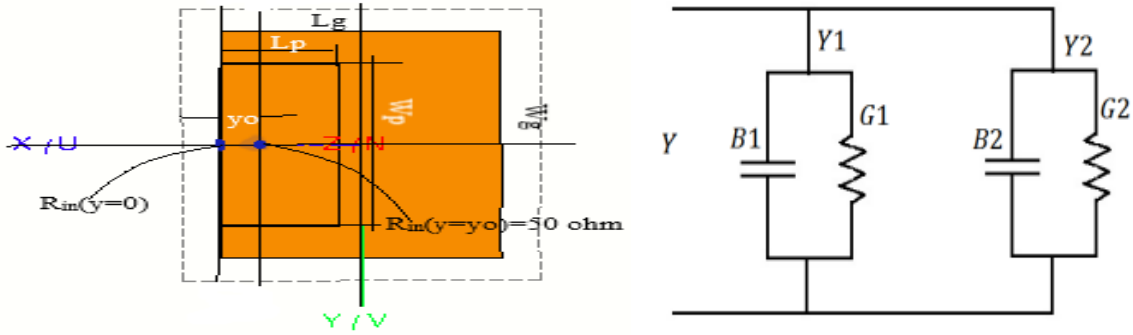


Figure 3.6: Feed Point Structure and Equivalent circuit

According to C. Balanis , taking into account the mutual effects of the parallel equivalent Admittance $Y1$ and $Y2$ shown in figure (3.6) and $G1$ and $G2$ are the conductance.

$$R_{in}(y=y_o) = R_{in}(y=0) * \cos^2\left(\frac{\pi}{L_p} y_o\right), \quad R_{in}(y=y_o) = 50\Omega \quad (3.22)$$

$$R_{in}(y=0) = \frac{1}{2(G_1 + G_2)} \quad (3.23)$$

$$G_{12} = \frac{1}{120\pi^2} \int_0^\pi \left[\frac{\sin\left(\frac{K_o W_p}{2} \cos \theta\right)}{\cos \theta} \right]^2 J_o(K_o L_p \sin \theta) \sin^3 \theta d\theta \quad (3.24)$$

$$G_1 = \frac{I_1}{120\pi^2}, \quad I_1 = \int_0^\pi \left[\frac{\sin\left(\frac{K_o W_p}{2} \cos \theta\right)}{\cos \theta} \right]^2 \sin^3 \theta d\theta \quad (3.25)$$

$$K_o = \frac{2\pi}{\lambda_o} \quad (3.26)$$

J_o is the Bessel function of the first kind of order zero.

y_o is computed from equation (3.22), therefore $y_o=0.22\text{mm}$

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Introduction

After selecting substrate, representing the design parameters, creating the PIFA array antenna, all of the configurations established in the preceding chapter are computer simulated using CADE-FEKO simulating software. By varying different parameters at the same operating frequency of the substrate material, the corresponding gain, directivity, return loss, beam width, band width, and radiation pattern of polarized PIFA microstrip antennas for single element, 4X1, and 4x4 PIFA array antennas are computed by performing relevant computer simulations for each of these situations separately.

In many researches, appropriate parameters are not analyzed and recommended for the official use of the PIFA. But in this thesis work, it was required to analyzed one of the basic parameters should be recommended with appropriate dimension with the desired V band frequency for cellular radio communication system. Based on the mathematical models the important parameters are analyzed by using the matlab software. The basic parameters that can affect the performance of the PIFA in this thesis work are width of shorting pin (W_s) and the gap between top plate and ground plate denoted by ' h_g '.

4.2. Parametric Study of Single PIFA Antenna

To select the suitable parameters that are basically affects the performance of the proposed antenna, was investigated depending on the simulated result. So that height (h_g), substrate thickness (h) and width of the shorting pin (W_s) are the essential parameters that can highly affects the proposed antenna performance. The simulation result was depicted as table below.

The broad parametric study was done by depending on the equation 3.1, $L_p + W_p - W_s = \lambda/4$. For better performance of the PIFA and since h is the height of the shorting pin or the slot between top plate and ground plate, we have;

$(L_p + W_p) - W_s - h = \lambda/4$. When h is the thickness of the substrate.

From the above equation wave length (λ) can be defined as; $\lambda = \frac{c}{f}$, f is the resonant frequency which is V-band frequency for this thesis. The frequency is remained constant and other all design parameter should be varied depending on the dimension of the W_s as well as h .

A. Effect of Air Gap (hg)

In order to analysis the effect of total length of the shorting pin or the gap between ground plane and top substrate on the performance of proposed antenna, the gap has been varied from 0.1 to 1.5 mm. The presented results given in Table 4.1 has revealed that height(h) of 1 mm can be consider as the suitable option to get the required results in terms of return loss, VSWR, bandwidth and gain.

Table 4.1: Effect of the variation of height on Proposed PIFA Performance

Height (hg) (mm)	Return Loss (dB)	VSWR	Gain (dB)	Beam width (deg)	Efficiency
0.1	-0.33	34.38	5.9	59.49	0.961
0.25	-0.43	32.19	7.5	100.95	0.985
0.5	-3.37	14.34	5.4	53.07	0.981
0.65	-3.18	14.85	4.83	46.87	0.993
1.0	-9.00	7.00	3.9	65.16	0.998
1.25	-4.51	11.91	5.92	56.73	0.912
1.5	-1.79	19.74	5.975	56.55	0.923

B. Effect of Substrate Thickness (h)

In order to analyze the effect of substrate thickness on the performance of proposed antenna, dimension of substrate thickness has been varied from 0.08 to 0.13 mm. The presented results are given in Table 4.2 has revealed that substrate thickness of 0.08, 0.09 and 0.1 mm has no significant different of the performance. Therefore, 0.1 mm can be consider as the suitable option to get the best results in terms of return loss, VSWR, bandwidth and gain.

Table 4.2 Effect of the variation of Substrate Thickness on Proposed PIFA Performance

Substrate Thickness (h) (mm)	Return Loss (dB)	VSWR	Gain (dB)	Beamwidth (deg)	Efficiency
0.08	-28.42	1.659	6.037	55.337	0.98
0.09	-28.48	1.654	6.000	56.527	0.99
0.1	-28.49	1.653	6.009	56.399	0.99
0.11	-20.46	1.724	6.001	54.917	0.99
0.12	-11.49	4.730	5.850	55.403	0.98
0.13	-14.41	3.345	5.827	56.614	0.98

C. Effect of Shorting Strip Width(Ws)

In order to analyses the effect of shorting strip on the performance of proposed antenna, dimension of strip width (Ws) has been varied from 0.08 to 1.13 mm. The presented results given in Table 4.3 has revealed that strip width of 1 mm can be consider as the suitable option to get the required results in terms of return loss, VSWR, bandwidth and gain.

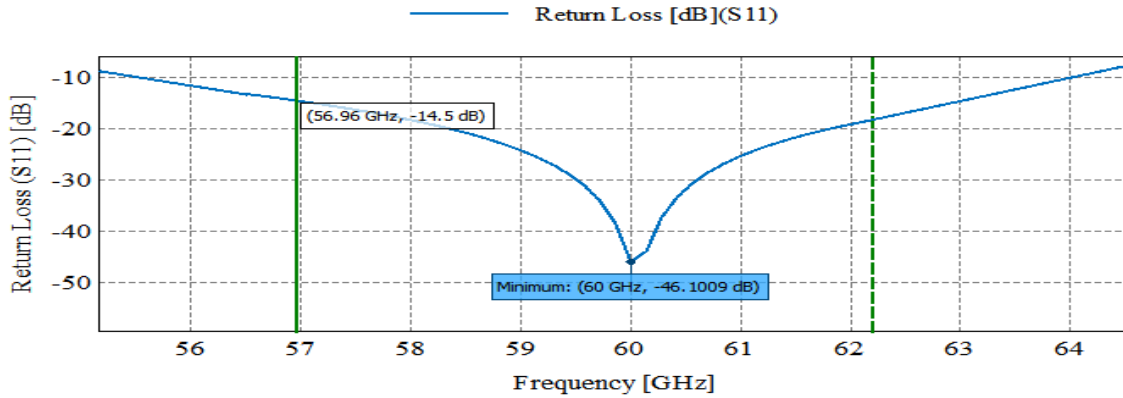
Table 4.3: Effect of the shorting Strip Width on Different parameters of PIFA (V band)

Ws (mm)	Return Loss (dB)	VSWR (dB)	Gain (dB)	Beamwidth (deg)	Efficiency
0.5	-23.2515	1.19662	5.9288	55.7008	0.992
0.6	-25.927	1.878	5.98	55.474	0.99
0.7	-29.8138	1.56144	6.0496	55.5903	0.9917
0.8	-30.757	1.504	6.1	54.785	0.98
0.9	-38.081	1.217	6.08	56.878	0.99
1.00	-46.106	1.0809	6.21985	54.1494	0.991
1.25	-25.9044	1.881	2.61	60.7818	0.990
1.5	-19.9681	1.74946	65584	53.0226	0.991

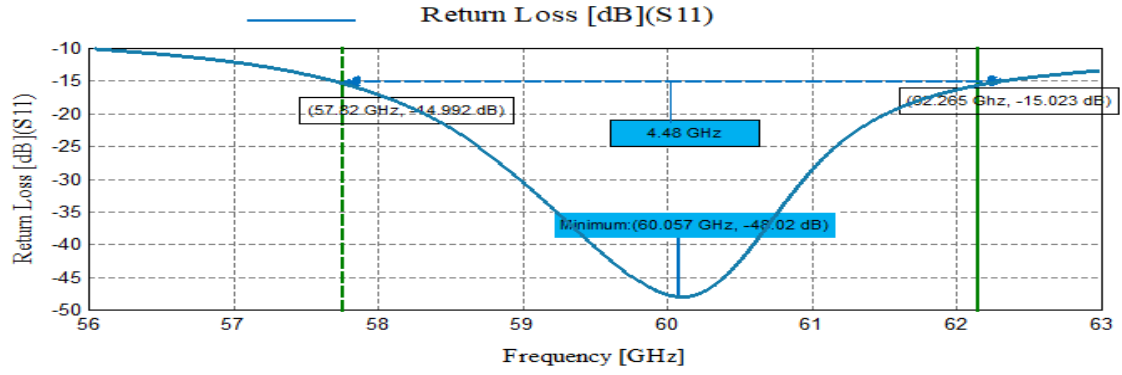
4.3 Simulation Result and Discussion

A. Return Loss

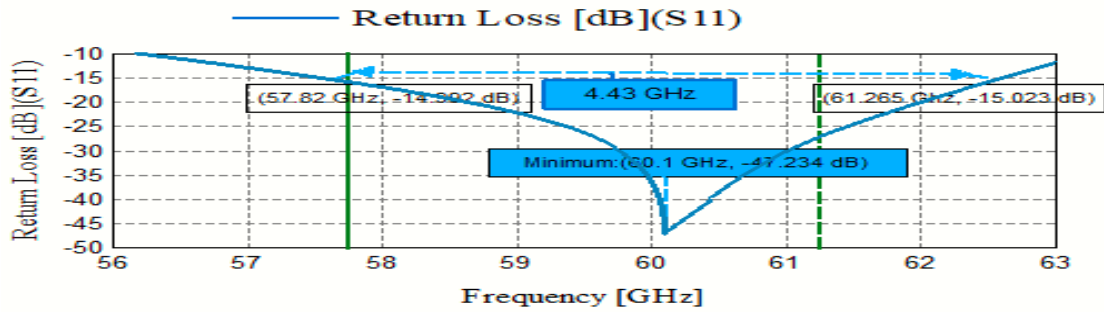
The simulated return loss (S_{11}) characteristics for proposed single element PIFA antenna are shown in Fig.4.1.a, b and c, from the graph, it can be seen that resonant frequencies at V-band (60GHz) achieved with return loss of -46.106dB, -48.02dB and -47.234dB for single, 4X1 and 4X4 PIFA array antenna respectively. From the results, represents 1X4 PIFA array antenna achieved very low return loss. Therefore, it can best satisfy for the cellular communication application.



a.



b.

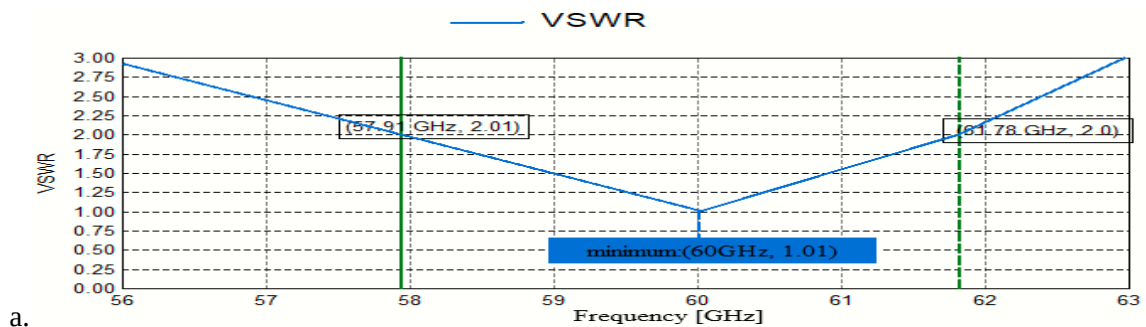


c.

Figure 4.1: Return Loss Versus Frequency (a) Single, (b) 1x4 and (c) 4X4 PIFA Antenna Array at V-band

B. VSWR (Voltage Standing Wave Ratio)

VSWR is a ratio of peak voltage to the minimum amplitude of voltage of standing wave. The VSWR is always a real and positive number for antennas. It is illustrated in figure 4.2 a, b, and c, at V-band (60 GHz) VSWR achieved as 1.01, 1.03 and 1.18 for single, 1x4 and 4x4 respectively. The source and load impedances are properly matched for optimal power transmission in the given circuit, all proposed designs were shown as flawlessly matched. Also it is observed from the results that at these resonant frequencies the VSWR is which are desirable for most of the wireless applications. Therefore, in this work all designed antenna was best for the desired application. The single is more matched than others.



a.

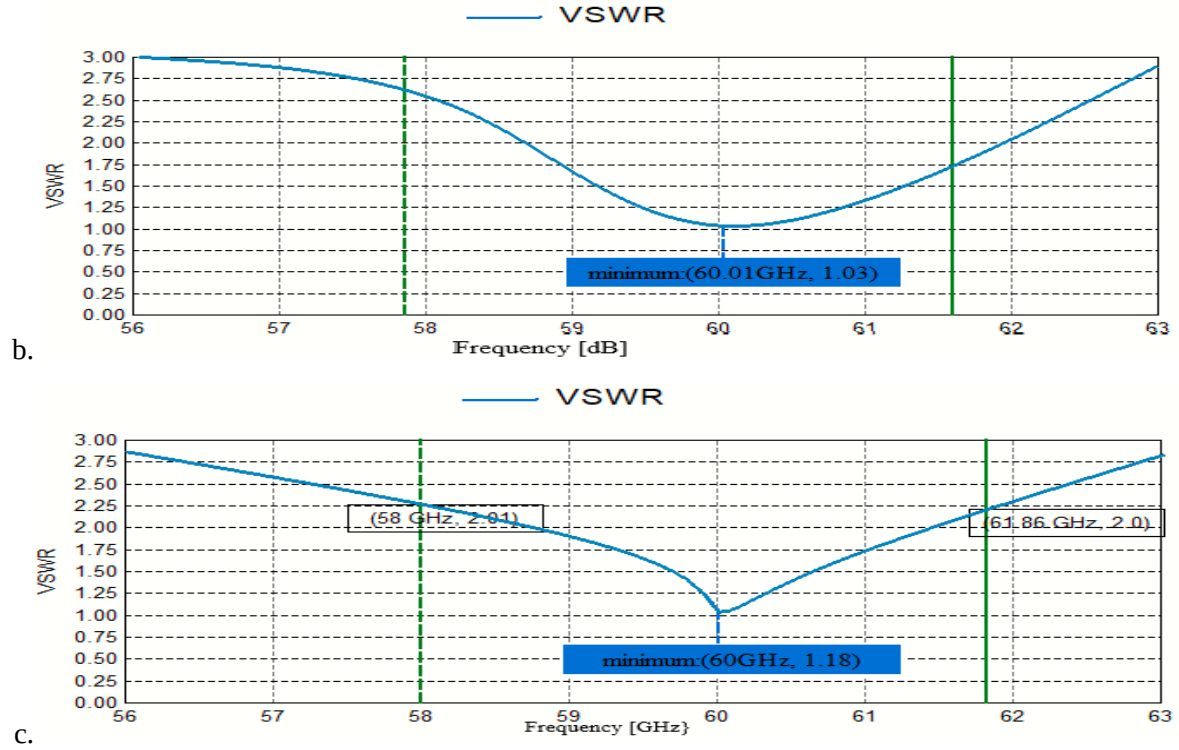


Figure 4.2: VSWR Versus Frequency for (a) Single, (b) 4X1 and (c) 4X4 PIFA Antenna Array at V-band

C. Bandwidth

The bandwidth of an antenna is defined as the range of frequencies where the return loss is larger than -10 dB. As a result, the antenna's bandwidth can be calculated using the return loss vs. frequency plot. Observed from the figure 4.3 a,b and c, the plot of VSWR versus frequency plots, the band width at $VSWR \leq 2$, ≤ 1.5 , ≤ 1.25 , and ≤ 1 can determined at the table 4.4 below.

The equation 4.1 is the optimal standard calculation expression for bandwidth. The calculated value below is the $VSWR \leq 2$ ($S_{11} \leq -10$).

$$\text{Bandwidth} = \frac{(f_H - f_L)}{f_r} * 100 \quad [4.1]$$

$$\text{Single PIFA: Bandwidth (\%)} = \frac{(61.78 - 57.97)}{60} * 100 = 3.81/60 * 100 = 6.35 \%$$

$$1X4 \text{ PIFA: Bandwidth (\%)} = \frac{(61.98 - 58.76)}{60} * 100 = 3.22/60 * 100 = 5.4 \%$$

$$4X4 \text{ PIFA: Bandwidth (\%)} = \frac{(61.56 - 58.87)}{60} * 100 = 2.69/60 * 100 = 4.48 \%$$

Therefore, the proposed antenna covers the corresponding bandwidth defined by $S_{11} < -10\text{dB}$ for this band is 6.35 % (3.81GHz), 5.4 % (3.22GHz) and 4.48 % (2.69GHz) for single element PIFA, 1x4 and 4X4 PIFA array antenna respectively. This all bandwidth satisfies the

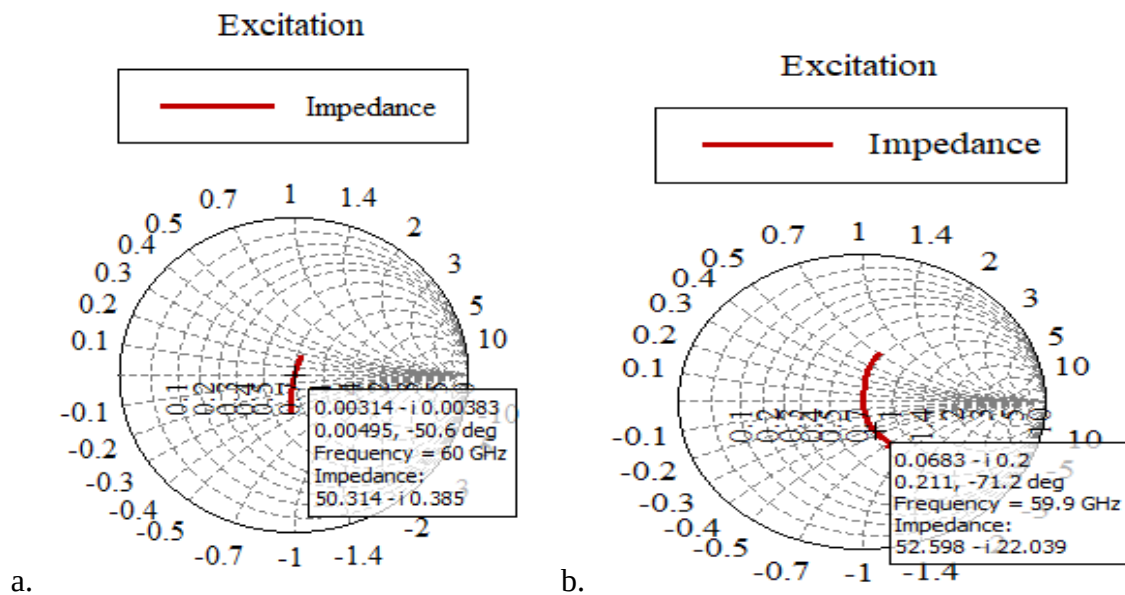
requirements for cellular radio communication applications and it is suitable for cellular base station.

Table 4.4: The Summary of Bandwidth with in VSWR

Configurations	VSWR	Bandwidth (GHz)
Single PIFA	1	NA
	1.25	0.98
	1.5	1.92
	2	3.81
1x4 PIFA	1	NA
	1.25	1.42
	1.5	2.21
	2	3.22
4x4 PIFA	1	NA
	1.25	0.61
	1.5	0.87
	2	2.69

D. Smith Chart Impedance Analysis

It represents the antenna as a circuit. The inductor value is on the upper side, the resistor value is on the middle, and the capacitor value is on the lower.



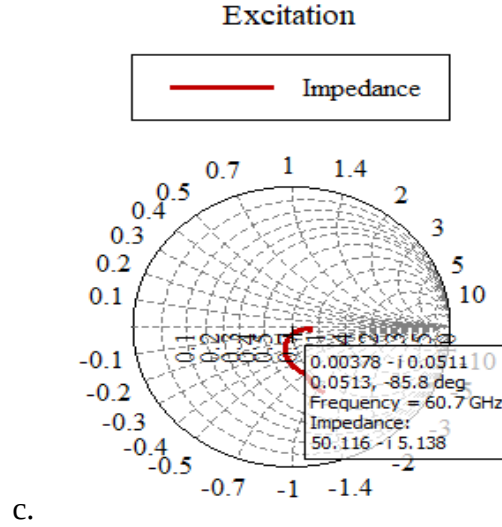


Figure 4.3: Smith Chart for (a) Single, (b) 1x4 and (c) 4x4 PIFA Antenna Array at 60GHz

The same input reflection coefficient (S_{11}) value is shown in figure 4.3 (a), (b) and (c) of the Smith chart. According to the Smith chart, the system's input impedance is also resistive. The marker indicates the system's impedance at its resonant frequency. From the smith chart the impedance of the single, 1x4 and 4x4 at resonant frequency shows best matched for all condition.

E. Directivity

As shown in figure 4.4, the simulated antenna radiates 10.0 dBi, 10.0 dBi, and 15.0 dBi, respectively, for single element, 1X4, and 4X4 PIFA array antennas (60 GHz). It demonstrates that the planned antenna has a higher gain in one direction than the isotropic antenna. Because it is a product of impedance mismatch loss and antenna efficiency, the antenna's overall radiation efficiency must be lower than the antenna's radiation.

NB: As shown from figure this is theta directivity only but not the total directivity. The total directivity was summarized at the summary of the result table.

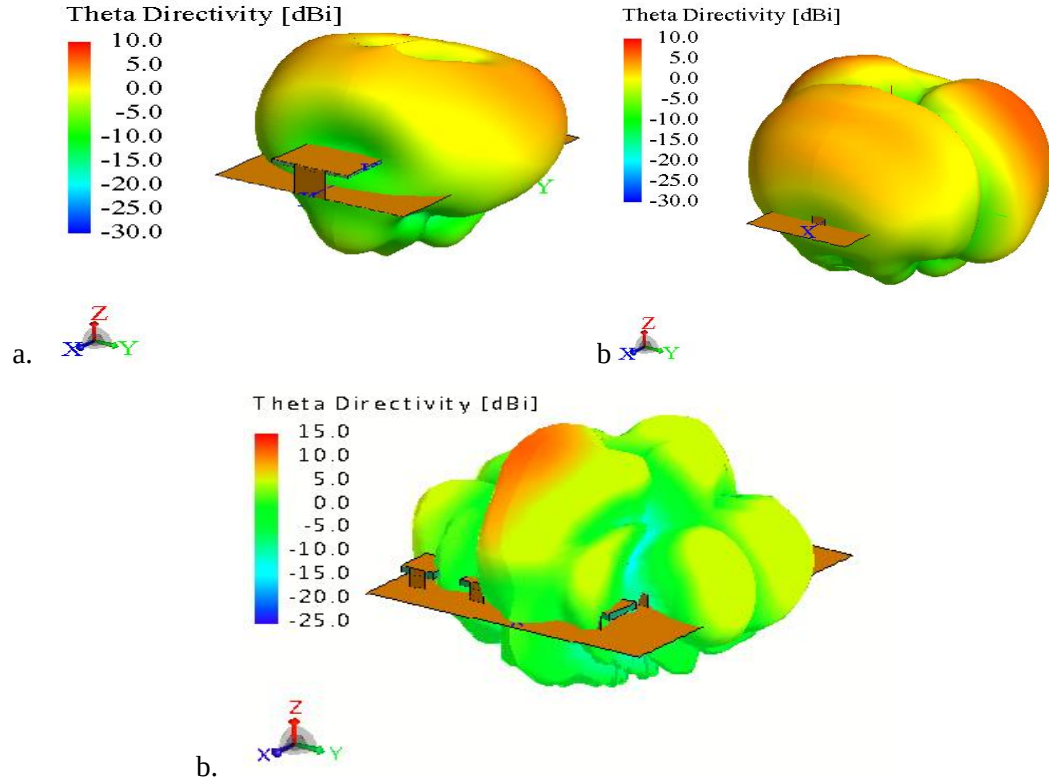
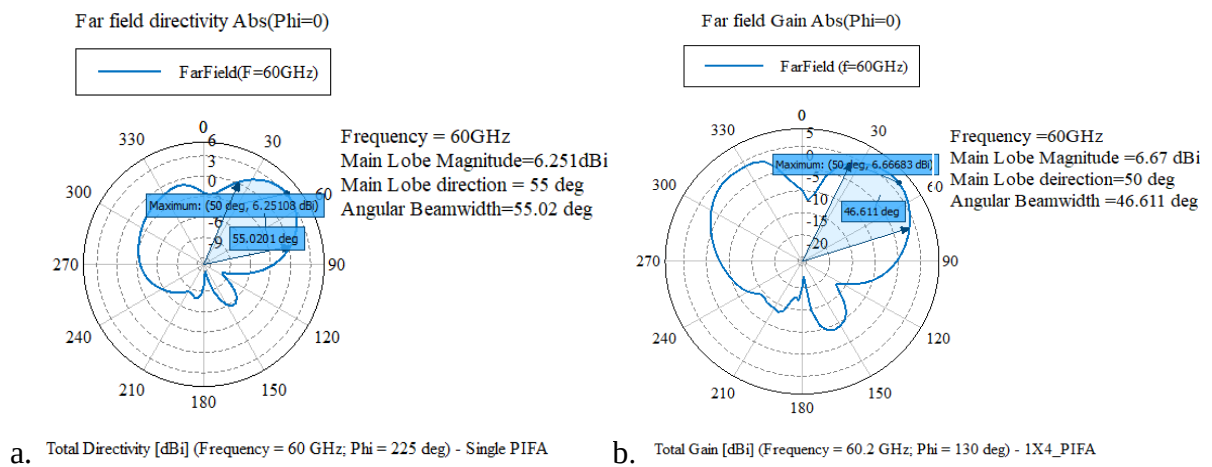


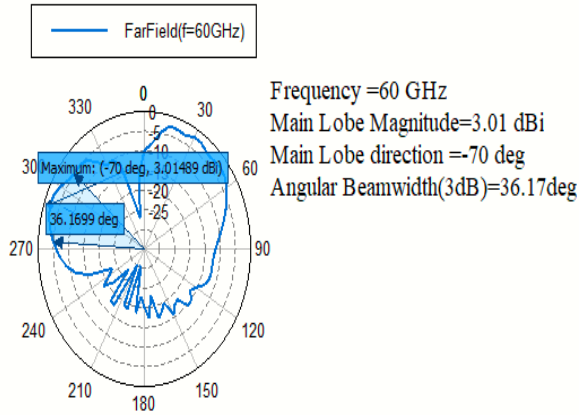
Figure 4.4: Theta directivity for (a) Single, (b) 1x4 and (c) 4X4 PIFA Array Antenna at 60 GHz

F. Radiation Pattern

Figure 4.5, illustrates that the antenna is a good radiator, radiating almost omnidirectional radiation and supporting a variety of standards.

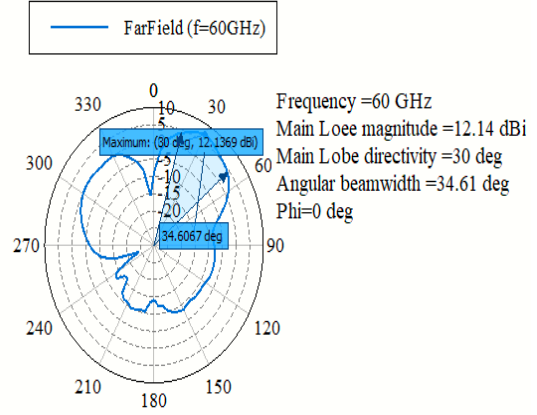


Far field Gain Abs(Phi=0 deg)



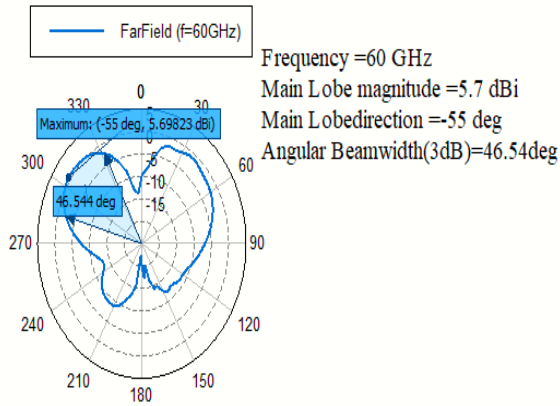
c. Total Gain [dBi] (Frequency = 60.2 GHz; Phi = 0 deg) - 1X4_PIFA

Far field Gain Abs(Phi=0 deg)



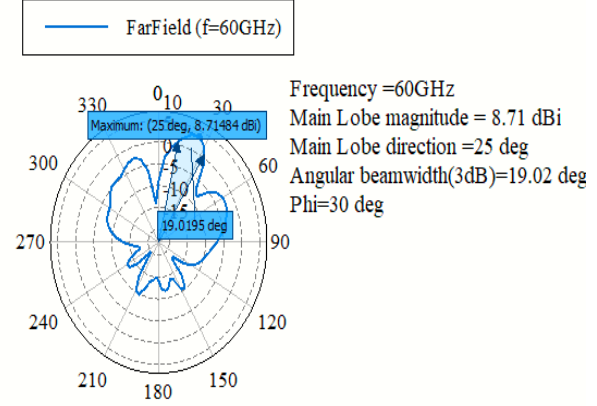
d. Total Gain [dBi] (Frequency = 60.175 GHz; Phi = 0 deg) - 4X4_PIFA

Far field Gain Abs(Phi=0 deg)



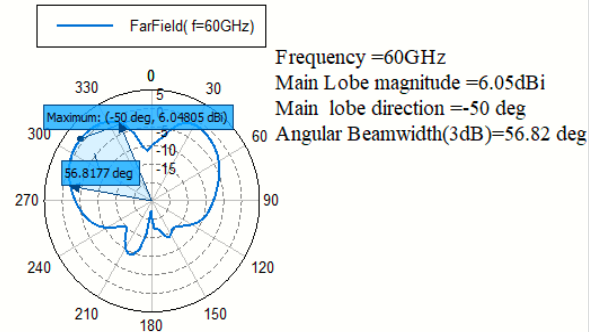
e. Total Gain [dBi] (Frequency = 60.2 GHz; Phi = 30 deg) - 1X4_PIFA

Far field Gain Abs (Phi=30 deg)



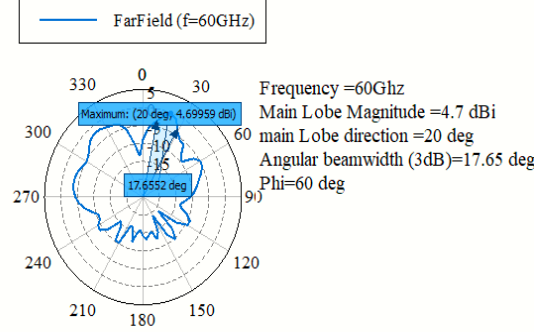
f. Total Gain [dBi] (Frequency = 60.175 GHz; Phi = 30 deg) - 4X4_PIFA

Far field Gain Abs(Phi=0 deg)



g. Total Gain [dBi] (Frequency = 60.2 GHz; Phi = 60 deg) - 1X4_PIFA

Far field Gain Abs(Phi=60 deg)



h. Total Gain [dBi] (Frequency = 60.175 GHz; Phi = 60 deg) - 4X4

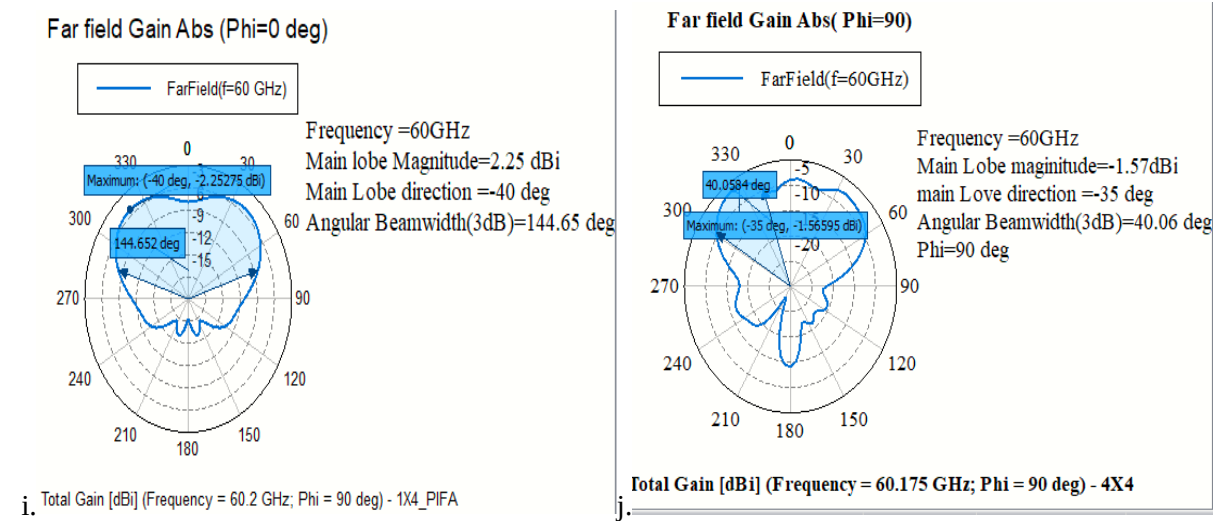


Figure 4.5: Radiation Pattern for Single, 4X1 and 4X4 PIFA Array Antenna at V-band (a-j)

Table 4. 5: Summary findings of the radiator pattern and beam steering for single, 1x4 and 4x4 at V-band

Figures	PIFA configuration	Finding			Steering angle(deg)
		Main Lobe magnitude(dBi)	Main lobe direction(deg)	Angular beam width(deg)	
a.	Single	6.25	55	55.02	45°
b.	1x4	6.67	50	46.611	130°
c.	1x4	3.01	-70	36.17	0°
d.	4x4	12.14	30	34.61	0°
e.	1x4	5.7	55	46.54	30°
f.	4x4	8.71	25	19.02	30°
g.	1x4	6.05	-50	56.82	60°
h.	4x4	4.7	20	17.65	60°
i.	1x4	2.25	-40	144.65	90°
j.	4x4	1.57	-35	40.06	90°

From the above table 4.5, illustrates the summary of the radiation pattern and beamsteering that have shown in figure 4.5. There for to decide the maximum gain and directivity at v-band PIFA was suitable for desired application with direction. 4x4 PIFA array was achieved gain 12.14 dBi at direction of the 0 degree. This is best to achieve the objectives of this thesis work.

G. Gain of PIFA antenna for far field

The antenna's gain and efficiency are the two most significant characteristics. An isotropic antenna that radiates in all directions has a larger antenna gain in one direction. Because antenna gain is determined by substrate thickness and relative dielectric constant, all MPAs have a small gain. Gain is proportional to the thickness of the substrate and inversely proportional to the

dielectric constant. The overall gain of the antenna was reached at V-band (60 GHz) operating frequency after simulating PIFA structures of 10.0 dBi, 10.0 dBi, and 15.0 dBi for single element, 1X4, and 4X4 PIFA array antennas, respectively. The proposed structure's gain is moderate, and it's good for the antenna's overall performance.

Antenna arrays are used to boost the antenna's overall gain. Different sorts of slots can also be employed to boost an antenna's total gain(Negi, 2016).

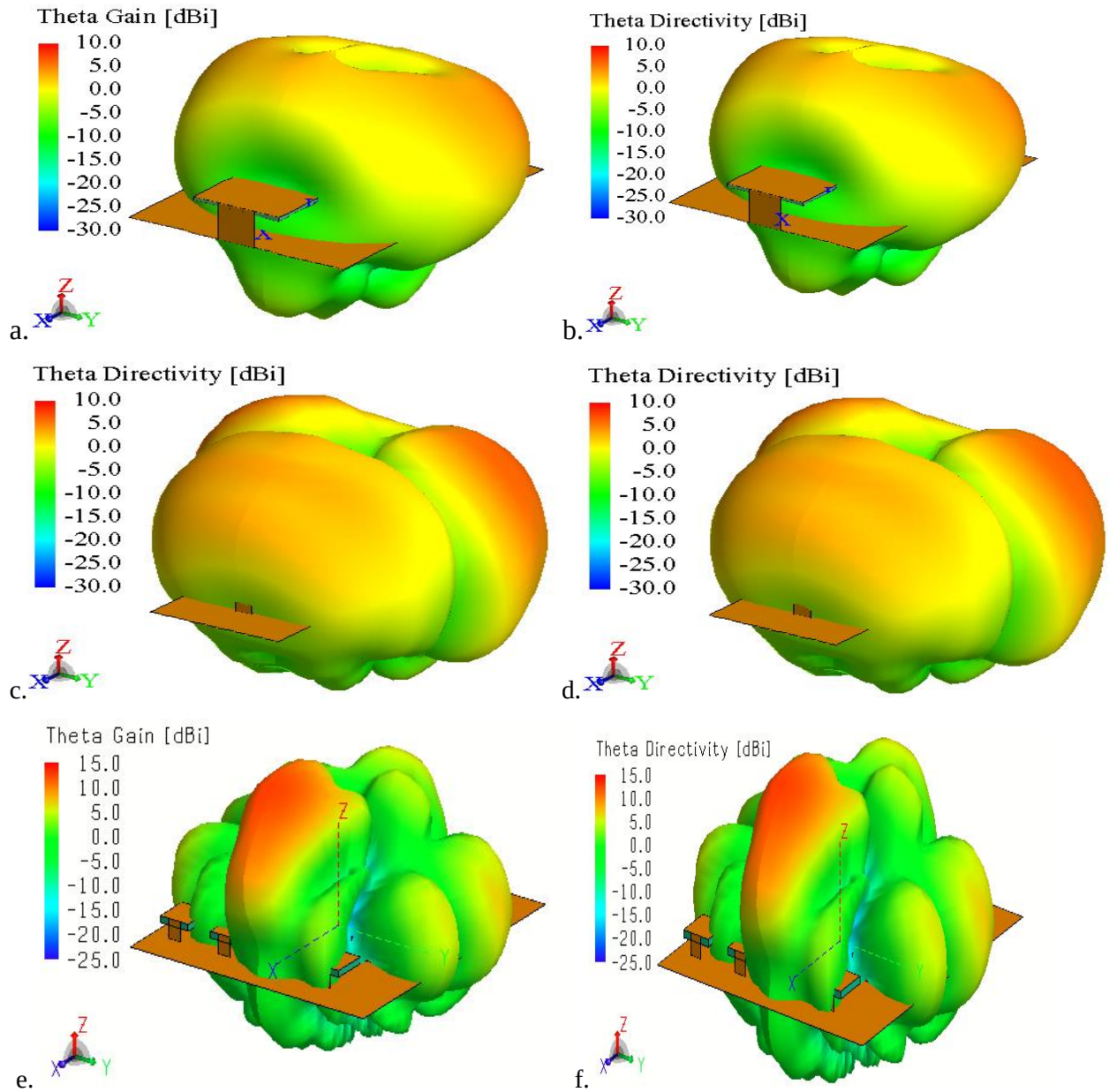


Figure 4.6: Theta Gain for Single, 1x4 and 4X4 PIFA Antenna Array at 60 GHz

Table 4.6: Validation of this work with other Base Station Antennas

The antenna that has been utilized for base station of various designs has been reviewed, as

Ref.	Antenna Type	Frequency (GHz)	Band Width (GHz)	VSWR	Gain (dBi)	Return Loss	Fabrication/ Installation /cost	HPBW
Chen et al., 2021	Dual-polarized Antenna	3.68	1.68	2	8.5 dBi	-20dB	Difficult/complex/high	60°-70°
Ciydem & Miran, 2020	Dual Polarization Suspended Patch Antenna	3.8	6.5	1.5	8.95 dBi	-15 dB	Difficult/complex/high	56°-65°
Alieldin, 2017	dual-polarized dipole antenna	2.45	3.63	1.5	8.3 dBi	-30 dB	Difficult/complex/high	60°-71°
Lian et al., 2015	Dual-Polarized Stepped Slot Antenna Array	1.55-2.5 GHz	3.4	2	13.9 dBi	-40dB	Difficult/complex/high	55°-70°
This work	PIFA	60 GHz	3.81	1.18	12.14 dBi	-48.02 dB	Easy/simple/low	40.6°

shown in table 4.6. Many studies have been conducted in order to improve the performance of the base station antenna for 5G networks. The antenna for 5G was designed in this thesis using the mmwave spectrum. According to table 4.6, this study outperformed all prior studies and suitable for a 5G mmWave base station.

4.4 Comparison of PIFA of Different Research Works and This Works

Table 4.7: Validation of this work with other base station

Ref.	Types of Antenna	Frequency (GHz)	Band Width	VSWR	Gain	Return Loss	Substrate type
Thu et al., 2020	Single PIFA for LEO Satellite	2.9GHz	510 MHz	1.2	4.79dBi	-18.4dB	FR-4
(Bousselmi & Gharsallah, 2019	Multi-Band PIFA Antenna for GPS	2.8GHz	0.20G Hz	1.667	3.2dBi	-12.02dB	FR-4
Amplier et al., 2017	A compact dual band MIMO PIFA for 5G	28GHz	1.3G Hz	1.04	8.62dB	-32.54dB	Air substrate
Nurul et al., 2019	Dual element MIMO PIFA for mmwave 5G	28 GHz	3.71 GHz	1.15	6.6 dB	-23 dB	RT/Duroid 5880
Haraz et al., 2015	Single PIFA Antenna for future 5G mobile	30.7GHz	2.08G Hz	1.005	10.1dB	-51.4dB	FR4.4
Rhee, 2020	Miniaturized PIFA for 5G Communication	2.17 GHz	1346M Hz	2.9	5.6dBi	-6.246	FR4
Ikram et al., 2018	PIFA Array With MIMO Configuration for 5G Mobile	28 GHz	1 Ghz	1.06	12 dBi	- 30 dB	RO-4350B
Rahman et al., 2014	4-element (PIFA) for Laptop and Wi-Fi application	2.45 GHz	2GHz	1.00	11.87 dB	-86.62 dB	silicon material
This work	Single PIFA	V-Band (60GHz)	3.81G Hz	1.01	6.25dBi	-46.1dB	FR4
	4X1 PIFA		3.22G Hz	1.03	6.67dBi	-48.02dB	FR4
	4X4 PIFA		2.69 GHz	1.18	12.14dBi	-47.23dB	FR4

As shown in table 4.7, many studies have been conducted for PIFA for different application with different techniques to improve the performance of the PIFA antenna for 5G networks. The PIFA antenna designed for 5G was designed in this thesis at V-band frequency spectrum. According to table 4.7, the developed 4x4 PIFA antenna outperformed all prior studies and is appropriate for a 5G mmWave and beyond.

4.5. Summary of Simulation Results

Table 4.8: Comparison analysis of single element, 1X4 and 4X4 PIFA Antenna Array at V band frequency (60GHz)

Parameters	Single Element PIFA	1X4 PIFA Array Antenna	4X4 PIFA array Antenna
Gain	6.25 dBi	6.67 dBi	12.14dBi
Directivity	7.21 dBi	7.03 dBi	13.12dBi
VSWR	1.01	1.03	1.18
Antenna Efficiency	86.68%	94.88%	92.53%
Band width	6.35 %(3.81GHz)	5.4 %(3.22GHz)	4.48 %(2.69GHz)
Return loss	-46.10dB	-48.02dB	-47.23dB
Beam width	55.02 deg	46.611 deg	34.61 deg

As shown by the overall overview of the suggested alternative PIFA designs in Table 4.8, the 4X4 PIFA array antenna outperformed the single and 1x4 PIFA in the majority of performance criteria. The performance of the 1X4 PIFA array antenna investigated in this study is good radiation pattern, low return loss, and more directives, and also the 4X4 PIFA array antenna is best than all others, according to the bandwidth efficiency with single PIFA antenna. This comparison is conducted using the same dialectic substrate with the same thickness and increasing the PIFA elements; the PIFA array antenna's directivity increases slightly, enhancing the bandwidth efficiency. As a result, the thesis proposal's purpose is achieved with high improvement of the antenna performance. These PIFA array antenna performance matrices compare to V-band about 60 GHz. This design's performance is comparable to all prior studies at lower band frequencies for base stations and other applications. This thesis contributes to visualization of return loss, beamforming, radiation pattern, and directivity improvement by developing single, 1X4, and 4X4 PIFA array antennas. For mmWave 5G wireless communications and other applications, all of the PIFA antenna designs described are strong rivals.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

When compared to standard microwave antennas, microstrip antennas are smaller, lighter, cheaper to construct, less costly, and easier to integrate into cellular networks. The Planar Inverted F-Antenna (PIFA) Antenna Array is designed and modelled in this study for mmWave MIMO Cellular Radio Communication with acceptable bandwidth enhancement at V-band frequency. An overview of relevant literature on PIFA antenna and how it could be used to improve the desired application follows the background information for the study. At V-band (60 GHz), a single, 1x4 and 4x4 PIFA antenna array for mmWave MIMO cellular communication has been successfully constructed, simulated, and analysed according to its design specifications. The design antenna's bandwidth, return loss, VSWR, and radiation pattern were all assessed.

The researcher came to a conclusion about the overall design in this chapter and looked into the findings. For minimum dielectric constant (i.e. FR-4), the gain, directivity, and patterning of a PIFA array antenna have been greatly improved. Modelling was done at several levels of design specifications in this study for a variety of PIFA antenna design. Various PIFA design factors (such as h_g , h , and W_s) were investigated and recommended in order to improve the PIFA design's performance. By altering several phase angles, the design was simulated to get the optimal result. Using probe feed (coaxial feed) approaches; the PIFA shape provides good directivity and simplicity in the design process. The beam created was successfully modelled and designed at V-band frequency utilizing CAD-FEKO and matlab2016a software for parameter computation based on the simulation obtained.

For its high gain, directivity, and bandwidth, it's ideal for efficiency, 4X4 element PIFA antenna arrays outperform single and 1x4 elements PIFA Antenna Array in comparison tests. So, despite its benefits, the PIFA antenna has significant role in wireless communication, such as cellular radio communication and advanced mobile handset devices, owing to its light weight, conformal nature, and low cost, and that the 60GHz frequency would be high frequency in world.

5.2. Recommendation and Future Attention

Gain, bandwidth, and directivity can all be fine-tuned or adjusted in the future for better results. The optimization technique is totally dependent on the field in which to utilize antenna, it is short-range communication or medical or military applications. The further optimization of design parameters in accordance with the requirements of latest technology updates. The following recommendations were made by the researcher based on the existing investigations.

- Using other tools for more parameter checking and better results is also a good idea. The fabrication process and experimental testing were still on-going.
- Furthermore, the PIFA antenna could be used in a MIMO configuration, and the design could be expanded to provide massive-MIMO transmission in the future.
- Two current cellular communication issues with base station antennas are fixed frequency with un-adjustable polarization and single band frequency of operation. As a result, developing an adaptable PIFA multiband antenna is critical for dealing with a slew of extra signal interference issues.
- Techniques to eliminate adjacent channel interference and the use of the circular polarized multi-band PIFA antenna for cellular communication are two of the PIFA's upcoming studies.

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